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**METEOROLOGICAL INSTRUMENTATION IN AIR
POLLUTION**

Ronald C. Hilfiker

**Environmental Protection Agency
Research Triangle Park, North Carolina**

1965

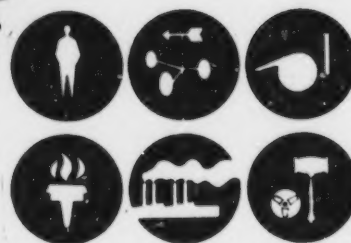
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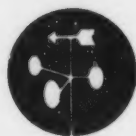
Meteorological Instrumentation in Air Pollution

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Meteorological Instrumentation in Air Pollution

Conducted by

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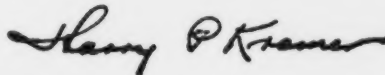
INSTITUTE FOR AIR POLLUTION TRAINING

MANPOWER DEVELOPMENT STAFF

The Institute for Air Pollution Training (1) conducts training for the development and improvement of State, regional, and local governmental air pollution control programs, (2) provides consultation and other training assistance to governmental agencies, educational institutions, industrial organizations, and others engaged in air pollution training activities and, (3) promotes the development and improvement of air pollution training programs in educational institutions and State, regional, and local governmental air pollution control agencies.

One of the principle mechanisms utilized to meet the Institute's goals is the intensive short-term technical training course. A full-time professional staff is responsible for the design, development, and presentation of these courses. In addition the services of scientists, engineers, and specialists from other EPA programs, governmental agencies, industry, and universities are used to augment and reinforce the Institute staff in the development and presentations of technical material.

Individual course objectives and desired learning outcomes are delineated to meet specific training needs. Subject matter areas covered include process evaluation and control, atmospheric sampling and analysis, field studies, and air quality management. These courses are presented in the Institute's resident classrooms and laboratories and at various field locations.



Harry P. Kramer, Sc.D
Director, Manpower Development Staff



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Section One

INTRODUCTION

Effects of Meteorological Parameters on Air Pollution

Meteorological Instrumentation at a Sample Site

General Instrumentation Requirements

Effects of Meteorological Parameters on Air Pollution

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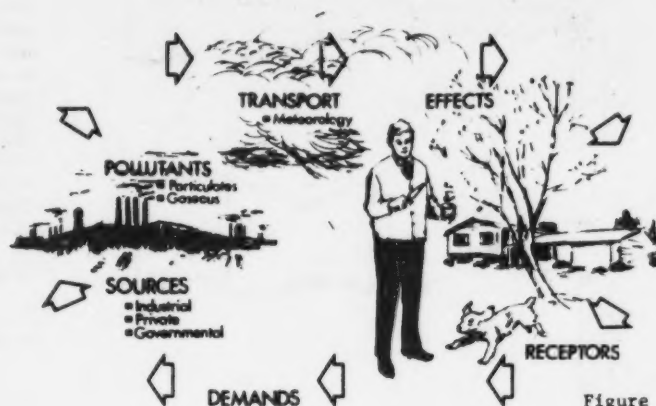


Figure 1.

The life cycle of air pollution is usually thought to consist of:

- 1) the release of air pollutants at the source
- 2) the transport and diffusion of the pollutants in the atmosphere
- 3) the reception of the air pollutants by plants, animals, man and inanimate objects

Figure 1 illustrates this life cycle.

The influence of meteorological factors is most pronounced during Phase 2 of the above life cycle. The meteorological factors of primary importance are:

- 1) wind speed
- 2) wind direction
- 3) temperature
- 4) atmospheric stability
- 5) precipitation

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Solar radiation, humidity, and pressure are of secondary importance. It should be noted, however, that the relative importance of the above parameters is dependent upon many factors such as geographic location, time of the year, etc.

WIND SPEED

Wind speed has two effects on air pollution:

- 1) travel time
- 2) dilution

The travel time is important in that it determines the amount of time the pollution is exposed to the above meteorological factors before coming into contact with the receptors.

The second effect of wind speed is on dilution of the pollutant in the downwind direction. If a continuous source is emitting a certain pollutant at a rate of 5 units/second, and the wind speed is 1 meter/second, then in a 1 meter segment of the downwind plume there will be 5 units of pollutant, since 1 meter of air moves past the source each second.

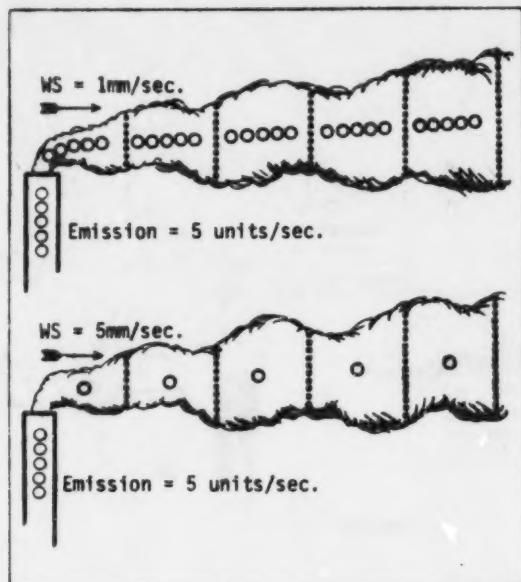


Figure 2. Affect of wind speed on dilution

Next, consider that the emission conditions are the same, but the wind speed is increased to 5 meters/second. In this case, a 1 meter segment of the downwind plume will only contain 1 unit of pollutant due to the fact that there are 5 meters of air moving past the source each second. Figure 2 illustrates this concept. From Figure 2 it can be seen that the dilution of air pollutants released from a source is directly proportional to wind speed, or, stated in another way, the downwind concentration of air pollutants is inversely proportional to wind speed.

WIND DIRECTION

The mean wind direction over a period of time will define which receptors will be affected by which sources during that time period. In other words, the mean wind direction will be indicative of the direction of travel of the pollutants. It must be remembered that in meteorology it is conventional to consider the wind direction as the direction from which the wind is blowing. Therefore, a north wind will transport pollutants to the south of the source.

TURBULENCE

In the preceding paragraphs, only the mean wind speed and direction have been considered. Some mention should be made of the deviations from these means. There are random velocity components in all directions with widely differing scales and periods. These random motions are responsible for the movement and diffusion of pollution about the mean downwind path. If the scale of this turbulent motion (the size of the eddy) is larger than the size of the pollutant plume in its vicinity, the eddy will move that portion of the plume. If the eddy is smaller than the plume, its effect is to diffuse or spread out the plume. Turbulence can be mechanically or thermally induced.

TEMPERATURE

The ambient temperature has several effects on air pollution:

- 1) temperature is related through the calculation of "degree-days" to the amount of fuel consumed for heating purposes.
- 2) ambient temperature at the pollutant source affects plume rise
- 3) chemical reaction rates in the atmosphere are influenced by ambient temperature

The most obvious effect of ambient temperature is on space heating requirements. The heating requirements for an average city in the mid to northern latitudes is increased by more than a factor of 20 in the transition from summer to winter. This increase in heating requirements is markedly reflected in the attendant discharge of certain pollutants into the atmosphere.

The well-known plume rise equations of Holland (1953) and others demonstrate that the rise of the plume above the stack is directly proportional to the difference between the stack gas temperature ($^{\circ}\text{K}$) and the ambient air temperature ($^{\circ}\text{K}$).

While it is known that chemical reaction rates in the atmosphere are influenced by ambient temperature, it is difficult to isolate the effects of temperature from those of solar radiation intensity.

Table 1.
COMPARISON OF TWO TYPES OF SMOG
(AFTER L. H. ROGERS)

Characteristic	Photochemical	London
Temperature at time of occurrence	75-90°F.	30-40°F.
Relative humidity	< 70%	85% (+ fog)
Type of temperature inversion	Subsidence	Radiation
Wind speed	< 5 mph	Calm
Visibility at time of maximum occurrence	< 1/2 to 1 mile	< 100 yards
Months of most probable occurrence	August-September	December-January
Major fuel used	Petroleum products	Coal and petroleum products
Principal components	Ozone, organic matter, nitrogen oxides, carbon monoxide	Sulfur compounds, particulate matter, carbon monoxide
Type of reactions	Photochemical plus thermal	Thermal
Effect on chemical reagents	Oxidation	Reduction
Time of maximum occurrence	Midday	Early morning
Principal effects on humans	Temporary eye irritation	Bronchial irritation; coughing; sometimes increased deaths among those with respiratory diseases

ATMOSPHERIC STABILITY

Stability in meteorology, as in everyday usage, refers to whether something in a state of equilibrium would, if disturbed, return to its undisturbed state, or increase its departure from equilibrium.

In meteorological terms atmospheric stability is defined in terms of the difference between the environmental temperature lapse rate and the dry adiabatic temperature lapse rate (-5.4°F per 1000 ft. or 1°C per 100m). The stability of the atmosphere affects plume shape and the capability of the atmosphere for dispersing contaminants. As such it serves as an index of atmospheric turbulence.

PRECIPITATION

Precipitation is one of the most important natural removal processes at work in the atmosphere. Precipitation removes contaminants from the atmosphere in one of two ways:

- 1) washcut
- 2) rainout

Washout is the interception and subsequent removal of particulates by falling raindrops. This process is effective on particles with a radius greater than 1μ . The larger the particle, the more effective washout becomes.

Rainout is the collection and subsequent removal from the atmosphere of particulates by cloud particles prior to their growth to and descent as raindrops. This process is effective in the size range $1\mu \leq r \leq 10\mu$.

SOLAR RADIATION, HUMIDITY, AND PRESSURE

Depending on the location, solar radiation and humidity can have a pronounced effect on the type and rate of chemical reactions that occur in the atmosphere. The different effects these two meteorological parameters can cause is probably best demonstrated by the comparison of the classic Los Angeles photochemical and London type smogs in Table 1.

Low and high pressure systems have predictable effects on air pollution potential due to the accompanying atmospheric stability associated with these systems.

Cyclones are characterized by:

- 1) uplifting of air
- 2) generally stormy weather
- 3) fast moving system - moderate to high winds

All of these factors are conducive to the good dispersion and natural removal of contaminants released into the atmosphere.

Anticyclones are characterized by:

- 1) subsidence of air (subsidence inversion)
- 2) generally fair weather
- 3) slow moving system - light to calm surface winds

All of these factors are conducive to the build-up of pollutants released into the atmosphere over a region.

Table 1 also points out the effect dominant pressure systems can have on the type of smog an area experiences.

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- 1) McCormick, R. A. "Air Pollution Climatology" in *Air Pollution*. Stern, A. C., Editor Academic Press, New York and London 1968
- 2) Turner, D. B., "Workbook of Atmospheric Dispersion Estimates" PHS Publication No. 99-AP-26
- 3) Holland, J. Z. "A Meteorological Survey of the Oak Ridge Area" 554-559 A. E. C. Report ORO-99, Washington, D. C. 584 pp.
- 4) Petterssen, S., "Introduction to Meteorology", McGraw Hill Co., New York, Toronto, London 1958

Meteorological Instrumentation at a Sampling Site

Ronald C. Hilfiker

All meteorological parameters affect the transport and dispersion of air pollutants to one degree or another. If one is faced with the problem of obtaining information on the pollutants in a particular area, a sampling site is usually set up in the area of interest at a position that will satisfactorily meet the sampling objectives.

Some typical sampling objectives are:

- 1) measure effects
- 2) control of air pollutants
- 3) obtain background information
- 4) locate a source of sources
- 5) evaluate trends

To fulfil any of these objectives, meteorological information about the air that is being sampled must be obtained. Without such data, the history of the pollutants that are collected is at best only a guess.

In this respect, a climatology of the area should be obtained. Hewson (1964) recommends a five-year record of wind speed and direction as an excellent basis for an air pollution climatology.

The air pollution climatology in an area can be influenced by one or more of the following:

- 1) regional weather patterns
- 2) local weather patterns (topography)
- 3) urban meteorology
- 4) aerodynamic effects

One must decide which of these factors is dominant in the region to be surveyed. If regional weather patterns are dominant, such as in the midwest plains or any other flat homogenous terrain, a five-year record from the local weather bureau station may be taken to apply directly to the sample site. However, if topographic, urban, or aerodynamic effects are dominant, a program of meteorological measurements at the site should be strongly considered. As a bare minimum, a month of meteorological data gathering should precede or coincide with pollution sampling.

METEOROLOGICAL MEASUREMENT SYSTEMS

A meteorological measurement system that is to support an air pollution study can take on an infinite variety of forms depending on the objective of the study, available funds and personnel, and the state of the instrumentation art. As a result, a simple listing of meteorological instruments that should be found at a sampling site cannot be made. Only general guidelines will be presented in this text, and it should be emphasized that professional meteorological consultation should be obtained in advance of each pollution study, not only for the purpose of deciding on instrumentation, but also for assistance in sample site selection.

Air pollution surveys covering a city-wide or regional area usually require a battery of sampling stations. The primary meteorological parameters of wind velocity, temperature, stability, and precipitation should either be monitored at each site or, if a group of sites is located in an area that is homogenous, a central meteorological station can service the group.

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Meteorological Instrumentation at a Sampling Site

Measurements of pressure would not be expected to differ to any great extent over a limited area such as a county or city. Therefore, in the interest of efficiency, pressure measurements can usually be made at a central location and applied to the entire survey.

Solar radiation measurements can also be made at a central location provided the network of sites is located entirely in an area where the pollution potential is uniform. It is a well documented fact that the intensity of solar radiation differs markedly between urban and rural areas due to the differences in average pollution concentrations.

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Meteorological Instruments at a Sampling Site

- 1) Hewson, E. W., "Industrial Air Pollution Meteorology" October 1964
- 2) "Considerations Affecting Steam Power Plant Site Selection" 1968, Appendix F
- 3) MacCready, Dr. P. B., Jr. "Design of Measurement Systems" in "Symposium - Environmental Measurements" PHS Publication No. 99-AP-15 - 1964

General Instrumentation Requirements

Ronald C. Hilfiker

"Precision Instruments", "Handsome Walnut Console", "High Degree of Accuracy", "Rugged Construction", "Black Crackle Finish", "Corrosion Resistant", and "Ultra-sensitivity" are among the many descriptive phrases used in instrumentation catalogs. Some of these attributes should be considered in detail, while others may be stereotyped as "window dressing".

The purchase of an instrument requires the consideration of two classes of requirements:

1. General Instrumentation Requirements
2. Specific Objective Oriented Requirements

There are many instrumentation requirements that will obviously depend on the specific objectives of the study that the instrument is to support. There are, however, a number of instrument requirements that should be considered before the purchase of any instrument. It is the purpose of this section to describe these general requirements so that a buyer will be able to distinguish between the instrumentation attributes that are important, and those that are only "window dressing".

RELIABILITY

Reliability is possibly the most important criterion for an instrument in continuous use. Regardless of how accurately an instrument is calibrated and read, it must be reliable to give reproducible results.

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ACCURACY

Accuracy is defined as the closeness of the instrument output reading to the true value of the parameter. The qualifications of an accurate instrument are as follows:

1. It is properly calibrated under known conditions
2. It has characteristics that are unchanging with time
3. The reactions of the instrument (dynamic response) to changes in the measured parameter are known to within the limits of error requirements

PRECISION

Precision is generally defined as the degree of closeness of a series of readings of an unchanging parameter. There often is confusion between the terms accuracy and precision. One way of clarifying their meanings is through the use of the "bulls eye" analogy. Figure 1 depicts this analogy.

SENSITIVITY

Sensitivity is defined as the smallest change in the measured variable that causes a detectable change in the output of the instrument.

General Instrumentation Requirements

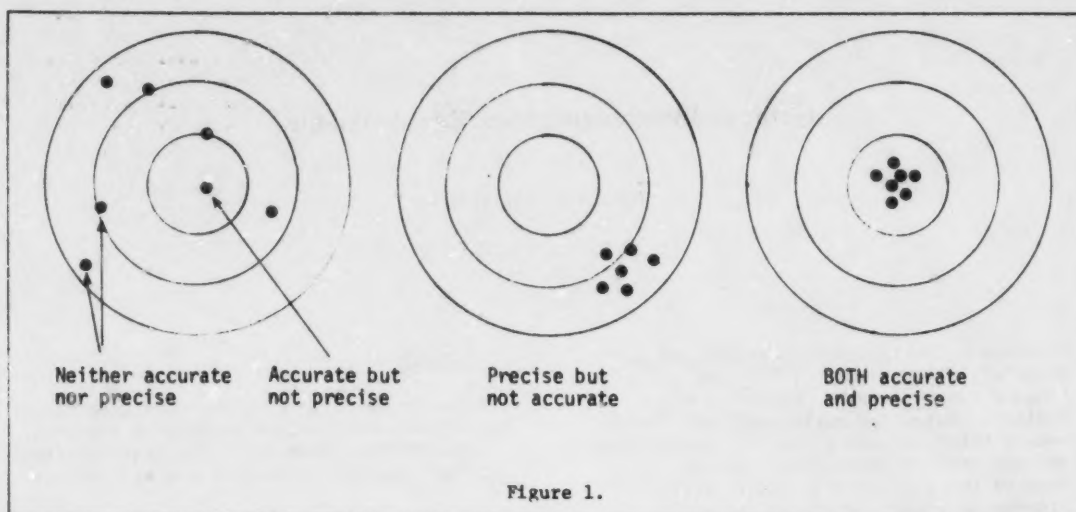


Figure 1.

SIMPLICITY

The lack of instrumentation experience among most observers makes this attribute a must for most meteorological instrumentation. The qualifications of a simple instrument are as follows:

1. Operational adjustments of the instrument should be simple
2. A simply written SOP manual should accompany the instrument
3. Adjustments that are not intended to be made by the purchaser should require a special tool

DURABILITY

Obviously, an instrument should be durable enough to survive vibrations and shock encountered in transportation, rough handling, etc. A meteorological instrument, in addition, should be able to perform reliably in all seasons of the year, and in a smoggy and corrosive atmosphere.

CONVENIENCE

Convenience of operation is definitely a must for an operational instrument. As a general rule, an instrument that is simple to operate is also convenient to operate.

Other requirements such as time constants, damping ratio, etc. are objective oriented, and will be covered in a later section.

Section Two

WIND MEASUREMENT

Surface Wind Speed Sensors

Surface Wind Direction Sensors

Wind Measuring Transducers

Measurement of Wind Aloft

Surface Wind Speed Sensors

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INTRODUCTION

A glance through the literature would reveal that there are many types of instruments for measuring wind speed.

Generally, wind speed sensors are broken down into the following categories:

1. Rotational anemometers
 - a. vertical shaft
 - b. horizontal shaft
2. Pressure anemometers
 - a. flat plate type anemometer
 - b. tube type anemometer
3. Bridled cup anemometer
4. Special types
 - a. hot wire anemometer
 - b. sonic anemometer
 - c. bivane
 - d. UVW anemometer

As will be shown, the rotational anemometers are the only types that satisfy all of the following desirable operational features:

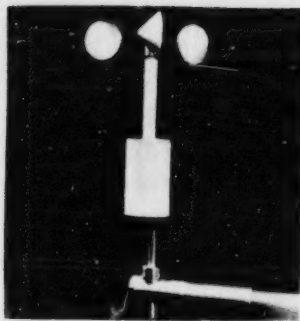
1. Essentially linear relationship between the sensor output and the wind speed.
2. Calibration is unaffected by changes in the temperature, pressure or humidity of the atmosphere.
3. Able to measure a wide range of wind speeds (<2 to 200 mph) [.9 to 90 m/s]
4. Long term calibration stability. The calibration often is unchanged after 10 years continuous operation.
5. Output of the sensor is easily adapted to remote indication.
6. Recording of the wind speed data is easily adaptable to either analog or digital form.
7. Generally require extremely little maintenance.

ROTATIONAL ANEMOMETERS

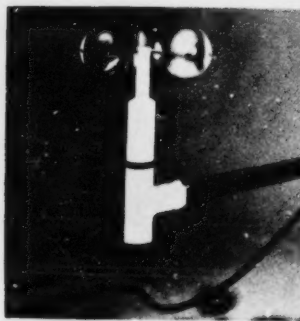
Vertical Shaft

A cup anemometer revolving about a vertical shaft is probably the most commonly used anemometer in use today. The most common of the cup anemometers are the 3 cup types shown in Figure 1.

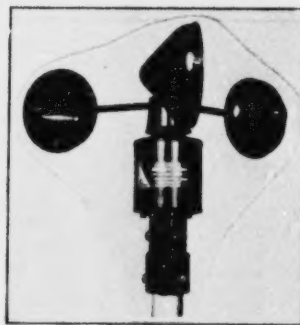
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(a) Climet Inst. Co.



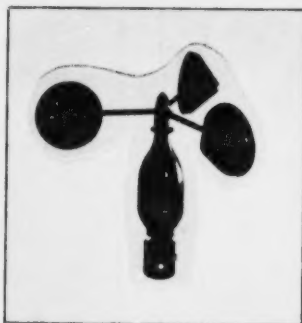
(b) R.M. Young Co.



(c) Belfort Inst. Co.



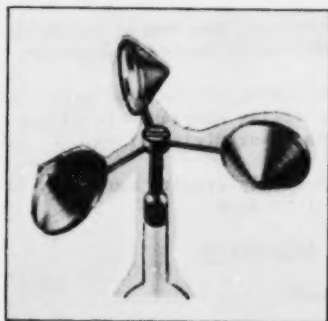
(d) Henry J. Green Co.



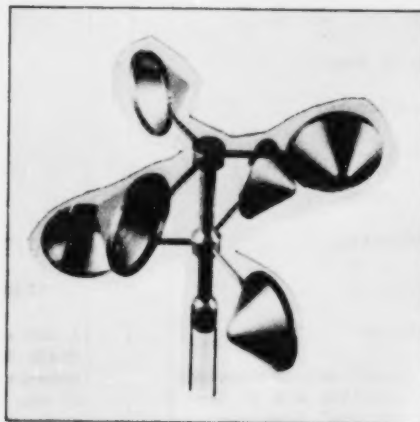
(e) Electric Speed Ind Co.



(f) Science Associates Inc.



(g) Teledyne-Geotech
(Bknn & Whtly)



(h) Teledyne-Geotech (Bknn & Whtly)

Figure 1.
Cup anemometers

Traditionally, anemometers have only had to yield average wind speeds for use in the support of aviation and weather forecasting operations. Sensors such as those in Figures 1c and 1e were developed with durability as the primary requirement. These cups are about 10 cm. in diameter with a moment arm of about 42 cm.

These anemometers, due to their large mass, have a relatively high starting speed (that wind speed at which the cups first begin to rotate or reach the manufacturers' accuracy specifications) of about 3 mph (1.4 m/s). This factor of high mass combined with a long moment arm will also produce a high moment of inertia which tends to cause the cups to indicate erroneous wind speeds under gusty conditions. Not only will the instantaneous readings be in error, but because the cups accelerate faster than they decelerate, the mean wind indicated may be slightly higher than the true speed.

With the advent of environmental concern, an anemometer was needed that would measure light winds, which are of great importance in air pollution meteorology. Also, to support turbulence and diffusion studies, an anemometer was needed that would approach giving an instantaneous response to wind speed fluctuations. Lightweight anemometers such as those in Figure 1a, 1b, and 1g were developed for such purposes.

To provide accuracy at low speeds and greater sensitivity, these small 3 cup anemometers are lightweight in construction (plastic or very thin aluminum) and employ a relatively short moment arm. In addition, friction has been reduced by utilizing miniature ball bearings and special type transmitters. The cups are generally 5 cm. in diameter and have a moment arm of about 7 cm. The result of these design considerations is more accurate instantaneous and average windspeeds.

An attempt at further reducing the starting speed is shown in Figure 1h. This cup wheel design, employing six staggered cups, yields a greater surface area exposed to the wind. This factor decreases the starting threshold from .75 mph (.35 m/s) (for the standard 3-cup of Figure 1g) to .4 - .5 mph (.2 - .25 m/s). This design also produces a more uniform torque around the entire shaft revolution.

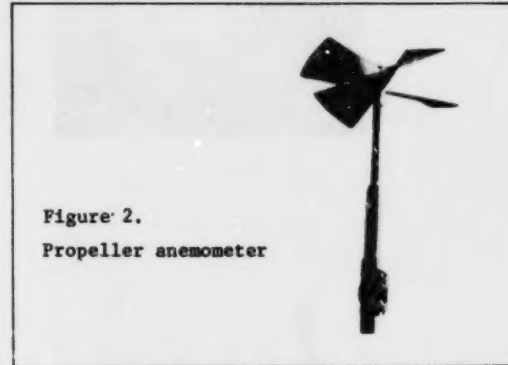


Figure 2.
Propeller anemometer

HORIZONTAL SHAFT

The second most commonly used wind speed measuring system is one that has a propeller on the end of a horizontal shaft that is oriented in to the wind by a vane on the opposite end of the shaft. A propeller anemometer is shown in Figure 2, and several propeller-vanes are shown in Figure 3.

These propellers are usually helicoidal in design with the rate of rotation of the propeller being linearly proportional to the wind speed. As with the cup anemometers, the propeller anemometers generally fall into two design categories:

1. Those designed with durability as a prime consideration (Figure 3c,d)
2. Those designed with sensitivity as a prime consideration (Figure 2, 3a,b)

The more sensitive propeller anemometers utilize lightweight aluminum or plastic as blade material, and generally employ either 2 or 4 blades. The two-bladed propellers (Figure 3b) have starting speeds of about .4 - .7 mph, (.2 - .35 m/s) while the 4-bladed propellers have a threshold of about .3 - .5 mph, (.15 - .25 m/s).

The more durable propeller anemometers use heavy gauge plastic or steel in the blade construction. Because of their relatively heavy mass, the 3-blade design of Figure 3c, d have higher starting speeds of about 2.5 - 3 mph, (1.2 - 1.5 m/s).

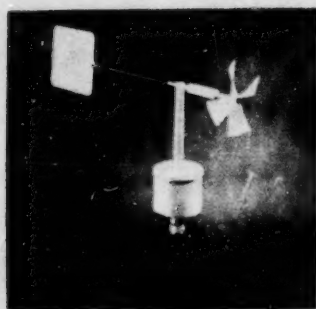


Figure 3. Propeller vanes

The sensitivity argument developed earlier for the cup anemometers also applies to propeller anemometers. However, because of the helicoidal design of the blades, the number of blades has no effect on the torque uniformity. The design produces a uniform torque independent of the number of propeller blades.

PRESSURE ANEMOMETERS

The measurement of the force exerted by the wind is another method of obtaining wind speed information. This is the oldest type of anemometer; the idea occurred to Leonardo Da Vinci (1500) and a description of such an instrument was published by Robert Hooke in 1667.

The force exerted by the wind can be employed to yield wind speed measurements in several ways:

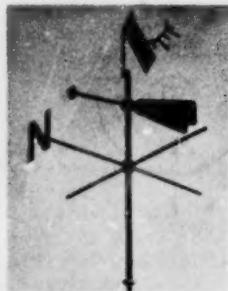
FLAT PLATE TYPE ANEMOMETER

The flat plate anemometer, or pressure plate anemometer as it is sometimes called, usually has two configurations:

1. Plate allowed to swing
2. Plate held stationary

A swinging flat plate anemometer is shown in Figure 4. This very crude device should only be used for obtaining "ball park" values of wind speed. As shown in Figure 4, the plate is kept oriented into the wind by an attached wind vane.

Figure 4.
Flat plate anemometer



If the plate is not allowed to swing, a pressure sensor could measure the force exerted on the plate by the wind. The force exerted by the wind is proportional to the square of the wind speed as follows:

$$F = C A \rho V^2$$

Where F = force exerted by the wind

C = proportionality constant
(dependent on the shape
and size of the plate)

A = area of the plate

ρ = density of the air

V = wind speed

The disadvantages of the flat plate anemometer are:

1. Lack of sensitivity
2. Output is proportional to the square of the wind speed
3. Output is affected by density changes which may be 20% or more during the course of a year.
4. Threshold speed is about 2 - 3 mph (1 - 1.5 m/s)

PRESSURE TUBE ANEMOMETER

Since early in the 18th century, it has been known that wind blowing into the mouth of a tube will cause an excess of pressure in the tube. This principle led to the de-

velopment of the pressure tube or pitot tube anemometer. This anemometer measures the difference in pressure between the dynamic opening at the tip and the static opening on the sides of the pitot-tube. Usually some form of manometer is used to measure this pressure difference. Figure 5 illustrates a pitot tube anemometer.

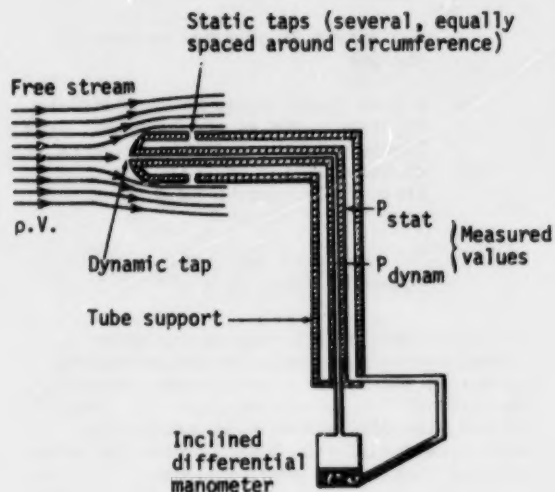


Figure 5. Pitot tube anemometer

The pitot-tube anemometer must be kept oriented into the wind with a vane. The wind speed is then given by the expression

$$V = \frac{2 (P_{DYNAM} - P_{STAT})}{\rho}$$

Where V = Wind Speed

P_{DYNAM} = Dynamic (Tip) Pressure

P_{STAT} = Static (side) Pressure

ρ = Air Density

Surface Wind Speed Sensors

The advantages of this type of sensor are as follows:

1. It is simple in design
2. It has no moving parts

The disadvantages of this type of sensor are as follows:

1. The sensitivity is dependent on the manometer or other pressure transducer
2. The output is affected by density changes
3. A true static pressure is difficult to measure due to the fact that wind blowing across an opening creates a suction, so the measured static pressure is somewhat less than the true static pressure
4. The output is proportional to the square of the wind speed

The pitot-tube is not used to any great extent for ordinary wind speed measurement in the United States. It is used, however, on aircraft for determination of the speed of the aircraft, and in wind tunnels for determination of tunnel wind speed, and most weather stations in Great Britain.

PRESSURE SPHERE ANEMOMETERS

Another type of pressure anemometer is the pressure sphere system which consists of a spherical probe with pressure ports drilled into its surface.

Figure 6 illustrates a front and cross section view of this system.

The pressure developed at the ports are transmitted through small tubes and measured by pressure transducers, usually strain gauges. The electrical output of these pressure transducers can be converted to the x, y and z components of the wind velocity. This feature enables the pressure sphere anemometer to yield the entire wind vector (speed and direction).

This sensor has the same advantages and disadvantages as the pitot-tube anemometer.

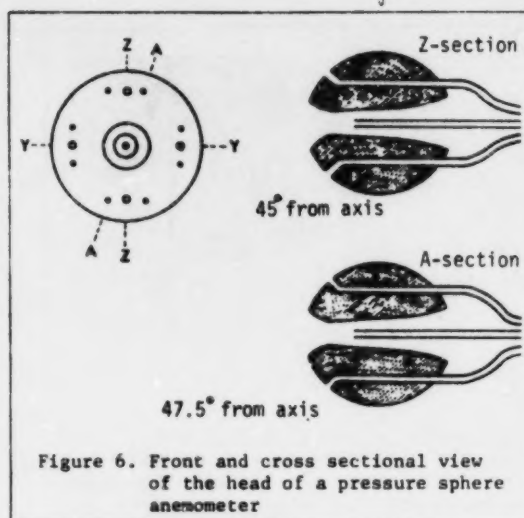


Figure 6. Front and cross sectional view of the head of a pressure sphere anemometer

BRIDLED CUP ANEMOMETERS

The rotational anemometers described in this section are turned by the force of the wind on the cups of propellers. Thus, if the cups are prevented from turning, the force necessary to prevent rotation is a measure of the wind speed. This restrained rotation is the principle on which the bridled cup anemometers is based.

This type of anemometer is generally not commercially available. Most of the bridled cup anemometers in existence have been custom made for specific research projects.

SPECIAL TYPES OF ANEMOMETERS

A. Hot Wire Anemometer

Historically, the hot wire anemometer has been used for many years as a research tool in fluid mechanics. It has been the traditional sensor for the measurement of turbulence.

Figure 7 shows various hot wire and hot film sensor configurations. The sensor relies on the principle of heat dissipation from the wire or film to the air around it. Since heat dissipation is proportional to the ventilation rate, wind speed can easily be determined.

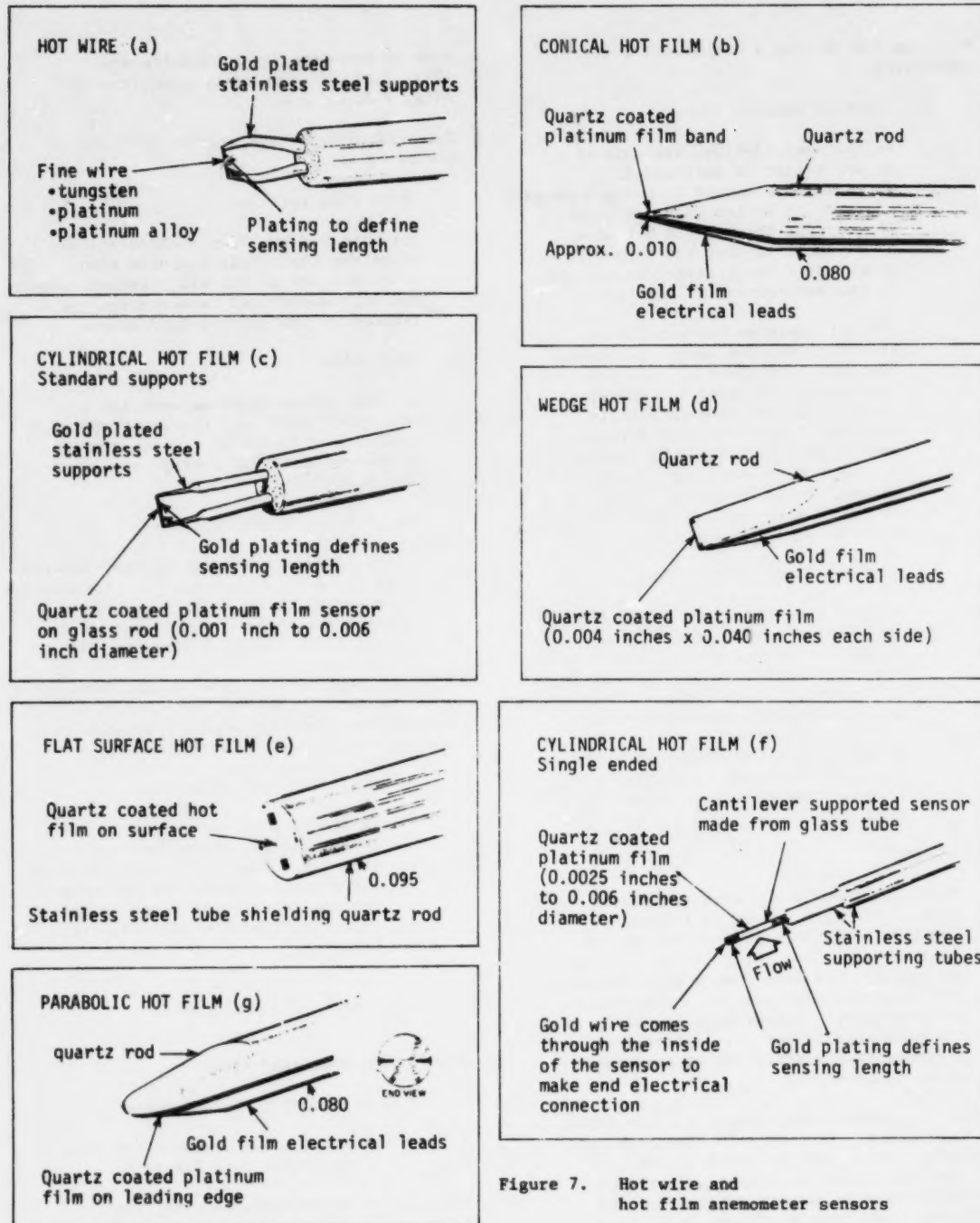


Figure 7. Hot wire and hot film anemometer sensors

Surface Wind Speed Sensors

There are two general types of hot wire anemometers:

1. Constant current type

As the name implies, the current to the sensor is maintained essentially constant by using a large resistor in series with the sensor. The current through the hot wire is adjusted so that the sensor is operated at the desired temperature in the environment of interest.

If heat transfer between the environment and the sensor increases (due to an increase in velocity) the sensor will tend to cool with a resulting decrease in its resistance. With constant current, this change in resistance causes a change in voltage across the sensor, and this voltage change is measured as an indication of a change in wind speed.

2. Constant Temperature Type

In this type of sensor the resistance change is compensated for by a change in current through the sensor. This compensation keeps the sensor at a constant temperature. The current change needed to produce this compensation is a function of air flow. The output of this type of anemometer is a measure of this current change converted to wind speed.

Probe Data

Figure 1a shows a hot wire anemometer probe. The wire sensor is typically .00015 - .0002 in (.0038 - .005 mm) in diameter and .04 - .08 in (1.0 - 2.0 mm) in length. The most common wire materials are tungsten, platinum and a platinum - iridium alloy. Tungsten is presently the more popular hot wire material with a temperature coefficient of resistance of about .004/°C.

Figure 7b-g shows some typical hotfilm probe configurations. The hot film dimensions are typically .004 x .040 in (.1 x 1.0 mm). The hot film sensor is essentially a conducting film on a ceramic substrate. The different probe configurations facilitate measurements in specialized applications

such as boundary layer measurements (Fig. 7 c), high velocity measurements (Fig. 7 d, g) etc.

The advantages of hot wire or film anemometers are as follows:

1. Short time constant

Hot wire and hot film anemometers are noted for their fast response time. Time constants are in the milli-second range and with electrical compensation can be reduced to the micro-second range.

2. Small size

As noted above these sensors can be made quite small and therefore approach measuring the wind at a point instead of the conventional average speed over a finite distance.

3. Good frequency response

A very fine hot wire can respond accurately to changes in wind speed at frequencies up to about 500 Hz. With electrical compensation this frequency can be increased to values of 300 to 500 KHz.

Although these sensors have enjoyed extensive use in research, they are not used to any great extent in operational situations because of the following disadvantages:

1. Not direction sensitive

If the flow is not normal to the sensor the resulting data are affected. The relationship between the actual velocity and the effective cooling velocity is given by the following equation and illustrated in Figure 8.

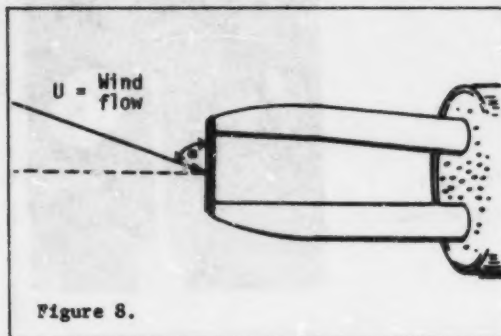
$$V^2 = U^2 (\sin^2 a + K^2 \cos^2 a)$$

where U = mean wind speed

V = effective cooling speed

a = angle between sensor and wind direction (see Figure 8)

K = coefficient relating the effectiveness of the velocity when it is parallel to the sensor



2. Non-linear Output

The basic output signal is a voltage which is related to flow as follows:

$$E^2 [A + B (\rho V)^{1/2}] (T_s - T_e)$$

where A & B = constants depending on fluid properties

ρ = air density

T_s = sensor operating temperature

T_e = environmental temperature

V = wind speed

This equation points out several disadvantages

- a. The output is proportional to the 4th root of the wind speed.
- b. Output is affected by changes in air density and temperature.
- c. The most non-linear portion of the output is at low wind speeds.

3. Subject to breakage by precipitation

Hot wire sensors are extremely fragile and can be easily broken by a raindrop. By using hot film sensors one can eliminate this disadvantage.

4. Subject to errors and calibration changes

Hot wires are notoriously troublesome in this regard. Their small size makes them susceptible to contamination and corrosion which easily destroys calibration.

The larger hot film sensor is a great improvement in this regard. The effects of surface contamination tend to be a function of sensor size, and a quartz coating on the sensor surface prevents corrosion and erosion.

As mentioned above, hot wire and hot film anemometers have found greatest application in situations where the environmental factors (density, temperature, etc.) can be controlled and calibrations frequently checked.

B. Sonic Anemometer

This type of system measures the time it takes for sound waves to travel over a known path length between the sound transmitter and sound receiver. Associated electronics translate this time into average wind speed values over this path length.

This type of system has two advantages:

- a. No moving parts
- b. Accurate at low wind speeds < 5 mph [2.3 m/s]

After approximately 20 years of research on this type of wind measurement system, a satisfactory operational system has not been developed.

Some disadvantages that have not yet been overcome are:

- a. System only measures component wind vector parallel to the sonic path. This can be overcome with a geometric array of path lengths but this accentuates the disadvantages that follow.
- b. Equipment is very complex and expensive
- c. Mutual interference problems with short path lengths.

As with the hot wire anemometer, the sonic anemometer has only found application in special research projects.

C. Propeller Bivane

These anemometers are capable of measuring the magnitude of the wind vector and will be discussed more fully in the wind direction sensor portion of this section.

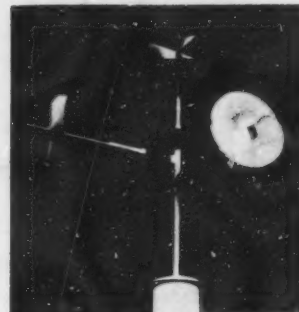
D. UVW Anemometer

Another sensor configuration that yields the wind vector and its fluctuations is the UVW anemometer. Figure 9 shows one type manufactured by R. M. Young Company.

In this sensor configuration, a propeller anemometer is mounted in each principal axis (thus the name UVW), and each yields the component wind vector in that axial direction. (See cosine response in Section III, Appendix C).

This anemometer has found limited operational use because of the sophisticated data reduction that is necessary to convert from an output of 3 wind speeds to a vector magnitude and direction.

Figure 9.
UVW anemometer



The UVW anemometer has, however, enjoyed easy application to those situations where the 3 component vectors are the only desired output, or where data reduction is accomplished through the use of a computer.

As with all sensors of the propeller type, serious error is introduced during periods of heavy precipitation, and with this particular propeller configuration there is some mutual interference error with certain wind directions.

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Surface Wind Direction Sensors

Ronald C. Hilfiker

INTRODUCTION

The measurement of wind direction is accomplished with an instrument known as a wind vane. Wind vanes are said to be the oldest of meteorological instruments. Blowing smoke or leaves probably led to the development of the first crude wind vane. Over the years, the evolution of technology has led to the wind vane as we know it today. Figure 1 shows the variety of wind vanes available today. Basically, a wind vane is a body mounted unsymmetrically about a vertical axis, on which it is free to turn. The end offering the least resistance to wind flow will point to windward.

These wind vanes are generally classed into 3 types:

- 1) Flat Plate Vane
- 2) Splayed Vane
- 3) Aerodynamic Shaped Vane

There are special kinds of wind vanes which serve a specialized purpose such as the wind sock or wind tee, one of which is in use at most airports. These wind vanes have the advantage of making the surface wind direction easily visible from the air.

This text will be limited to a discussion of the 3 basic types of vanes listed above.

FLAT PLATE VANE

Typical flat plate vanes are shown in Figure 1 a, b, c, d, g, i, k, and l. The term flat plate refers to the tail shape which is simply a flat plate. The flat plate can take on a number of different shapes and be made out of a number of different materials.

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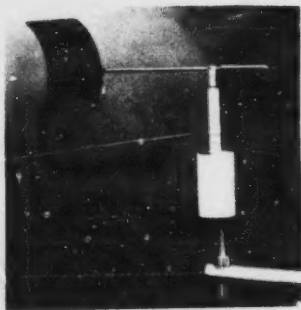
As with wind speed sensors, the material used in constructing the wind vane will generally determine the proper use of the vane. Vanes made of heavy gauge metal or plastic such as Figure 1 g should only be used for obtaining average wind direction. The large mass creates a high moment of inertia which will give, under certain conditions, a much higher indication of wind fluctuations than actually exists.

The lightweight sensitive vanes of Figure 1 a, b, d, k and l have tails made of thin gauge aluminum or plastic or molded expanded polystyrene. The counterweights are also close to the center of rotation. This design creates a highly sensitive vane that can be suitably used for turbulence or other fine analyses of the wind trace.

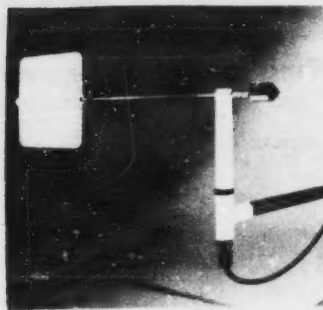
SPLAYED VANE

Typical splayed vanes are shown in Figure 1 e, f, h, and p. In this type of vane, two flat plates are joined at a small angle (usually about 15°) at one end of the horizontal shaft. This design came about through experimentation that showed that the splayed vane followed small changes in wind direction better than the flat plate. However, the increased mass incurred by two flat plates makes this type of vane unsuitable for anything but the measurement of average wind direction.

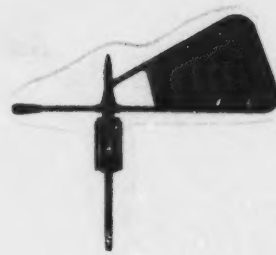
The splayed vane of Figure 1 e has, mainly because of its durability and reliability, found widespread use in its role as the main wind direction sensor for the National Weather Service. Therefore, it should be noted that wind direction data obtained from a National Weather Service Station should be used only as an indication of average wind direction.



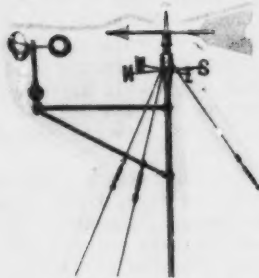
Climet Inst. Co. (a)



R.M. Young Co. (b)



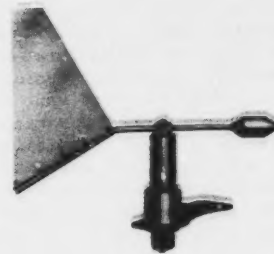
Belfort Inst. Co. (c)



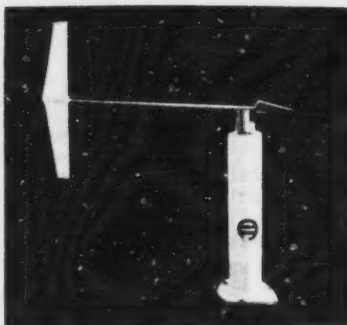
Science Associates Inc. (g)



Epic Co. (h)



Epic Co. (i)



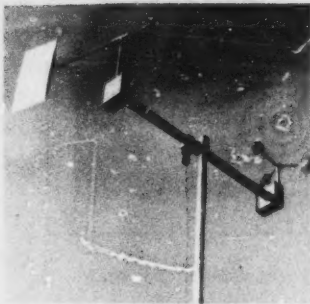
Teledyne-Geotech (l)



Bendix Co. (m)



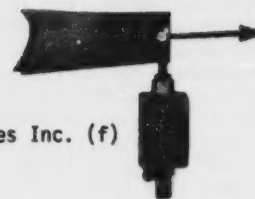
Belfort Inst. Co. (n)



Wong Lab. (d)



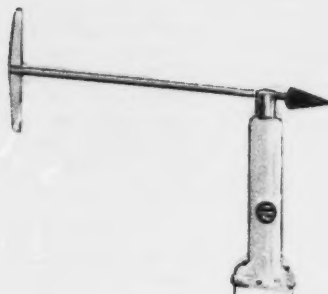
Electric Speed Indicator Co. (e)



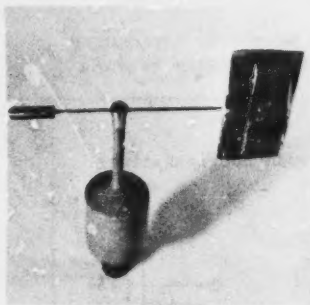
Science Associates Inc. (f)



Teledyne-Geotech (j)



Teledyne-Geotech (k)



Raim Inst. Co. (o)



Epic Co. (p)

● Figure 1. Wind Vanes

AERODYNAMIC SHAPED VANE

This type of wind vane is shown in Figure 1 j, m, n, and o. The aerodynamic shaped vane has an airfoil cross section. This type of vane has been shown to produce up to 15% more torque for certain ranges of attack angles than a flat plate vane of similar physical dimensions.

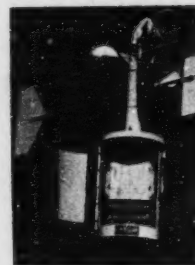
This type of design, as with the splayed vane, incorporates more mass than the flat plate vane and therefore produces a higher moment of inertia yielding a poor dynamic performance. An aerodynamic wind vane that has found widespread use in air pollution studies is shown in Figure 1 m, i. This device is commonly called an "aero vane". It should be remembered that its dynamic performance is inferior to the sensitive vanes of Figure 10a, b, d, k, l, and the use of the data gathered by the "aero vane" should reflect this fact.

There are modifications of the above 3 types of wind vanes in existence. A modification of the flat plate vane is shown in Figure 2. The wind vane in this system is provided with a "nose damping vane" which alters the damping ratio (see Section 3) and improves its dynamic performance.

A modification of the splayed vane is shown in Figure 1 p. These vanes, called double-fin vanes, employ two flat plates, as in the splayed vane, connected by one or more struts. Different configurations of the double-fin vanes are shown in Figure 3.

In a recent study by Wieringa and Van Lindert (1971) this type of vane was found to exhibit two equilibrium positions at opposite angles to the main air flow

Figure 2.
Mechanical
weather station



direction. Obviously, this is a critical disadvantage.

BI-DIRECTIONAL VANES

All of the above mentioned wind vanes measure only the horizontal component of the wind vector. Many applications require information about the vertical component of the wind vector. An instrument that measures the horizontal and vertical wind direction is called a Bi-Directional Vane (Bi-Vane), and is illustrated in Figure 3.

This type of vane has a tail composed of two flat plate tails mounted perpendicular to one another. The vane has the freedom to move in the vertical (within limits of $N+60^\circ$ to -60°) as well as the horizontal (full 360°). The transducers used are the same as for a standard vane, and will be covered in the next section.

The addition of a propeller anemometer to the Bi-Vane, as shown in Figure 4, en-

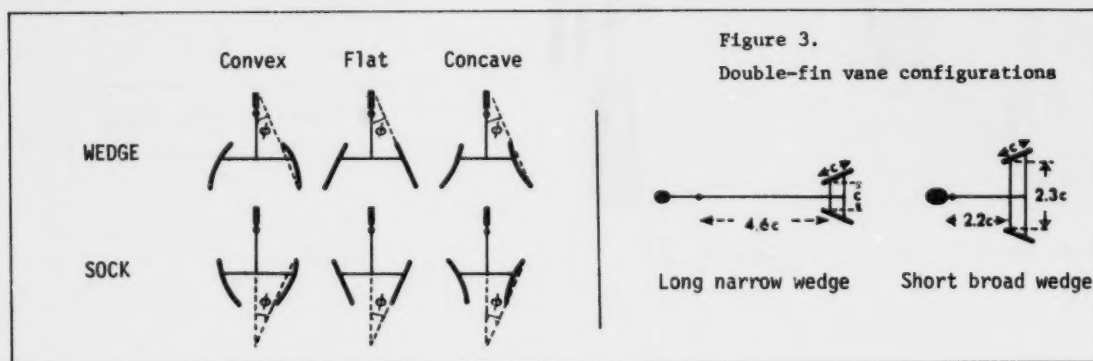


Figure 3.
Double-fin vane configurations

ables the instrument to measure the entire wind vector (wind velocity), composed of the vector orientation (horizontal and vertical direction) as well as the absolute wind speed. The instrument as shown in Figure 5 is called a propeller bi-vane.

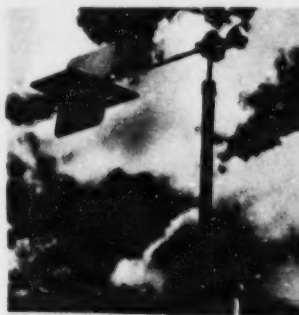


Figure 4. Bi-Vane with a propeller anemometer



Figure 5. Propeller Bi-Vane

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Wind Measuring Transducers

Ronald C. Hilfiker

INTRODUCTION

The measurement of wind consists of the transfer of energy contained in the moving stream of air from one component in the measurement system to the next until a final display on the readout instrument is obtained. Since the kinetic energy contained in the moving stream of air is not easily transmitted or recorded, a device must be used which will convert the kinetic energy in the air stream to a type of energy that can be easily transmitted and recorded. This converting device is called a transducer and the energy change process is called transduction.

In every measurement system one can distinguish between different transducer types. One of the easiest ways to do this is by function. This manner of classifying transducers results in the following categories:

- 1) Input or measuring transducers
- 2) Modifying transducers
- 3) Output or readout transducers

In this section we will limit our discussion to input or measuring transducer types. Modifying transducers act on the output of the measuring transducers. The most common example of a modifying transducer is the electronic amplifier. The output or readout transducer transforms the modified signal into a form that can be detected by the human senses. The usual form is a visual display, and the usual transducer is a meter movement in the form of a galvanometer, dial indicator, etc.

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MEASURING TRANSDUCERS

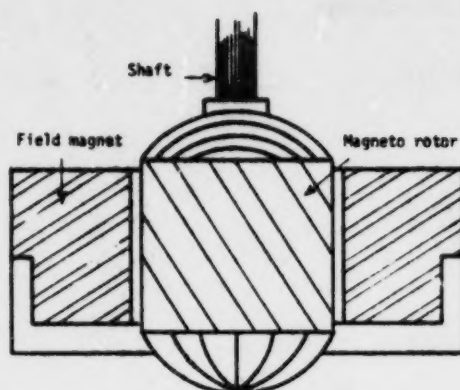
A. Wind Speed

The most common aerodynamic sensor for the measurement of wind speed is the cup or propeller. The wind speed measuring transducer must convert this cup or propeller rotation to an energy form that is easily transmittable. The energy form is usually electric and the transducer is commonly one of four types.

1. D. C. generator

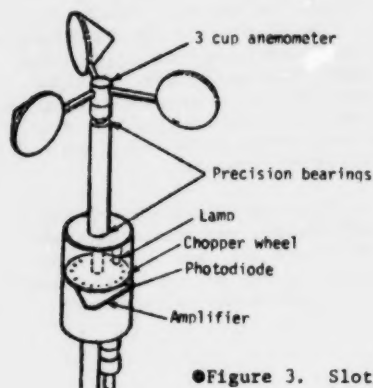
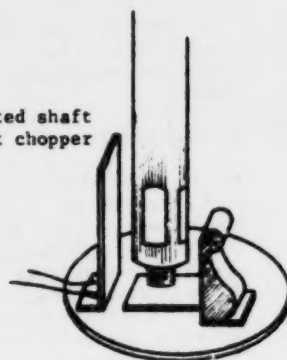
Small, permanent field generators are used that have an output that is linearly proportional to the rate of turning of the cup or propeller and hence is linearly proportional to the wind speed. The main disadvantage of D. C. generators is the relatively high starting or threshold speeds. The brush and bearing friction combine to produce a lower limit to the threshold speed of about 1 mph (.5 m/s) on the most sensitive systems. The brushes on these generators usually need servicing only about once a year under continuous use. On some of the more sensitive sensors the unit is sealed and it is recommended that the unit be sent to the factory for servicing or replaced completely.

Figure 1. illustrates a typical D. C. generator (brushes not shown) from the sensor of Figure 1e. The output from this transducer can be recorded directly on any D. C. galvanometer recorder.



●Figure 1. D.C. Tachometer generator

●Figure 2. Slotted shaft light chopper



●Figure 3. Slotted disk light chopper

2. A. C. generator

In an attempt to lower the threshold speed by eliminating brush friction, some manufacturers are using A.C. generators instead of D. C. generators. A.C. generators reduce the friction considerably and eliminate brush and commutator maintenance. A.C. generators are available with either two, four, six or eight-pole permanent magnet rotors. The larger the number of poles, the more pulses are available per shaft revolution, producing a smoother record.

The largest disadvantage of the A.C. generator is associated with the number of pulses per shaft revolution. These pulses must be rectified by a modifying transducer (rectifier) in order to have a suitable energy form for recording. Low wind speeds generate a low frequency of A.C. pulses and normal rectifiers do not function properly with a low frequency input. Thus, spurious oscillations may be produced at low wind speeds. Therefore, to obtain wind speeds below about 2/m/sec (4 mph) some sort of electronic correction is needed.

This disadvantage defeats the purpose of reducing the friction and has therefore resulted in a minimal use of this type of transducer.

3. Interrupted light beam

Further reduction in friction with accompanying lower threshold speed and quicker response can be accomplished with the use of an interrupted light beam (light chopper) transducer. This transducer employs either a slotted shaft (Figure 2.) or a slotted disk (Figure 3.), a light source and a photocell or photo-diode. The cup or propeller rotates the slotted shaft or disc and a pulse is created each time a slot allows light from the source on one side of the shaft or disk to fall on the photocell on the other side of the shaft or disk. The larger the number of slots in the shaft or disk, the smoother will be the output, especially at low wind speeds. The output from the transducer is handled in the same manner as the output from the A.C. generator. The large number of slots (about 100) prevent spurious oscillations in the output at low wind speeds. The

the sensors (Surface Wind Speed Sensors, Figure 1a and 1g, page 2-2) utilize this type of transducer.

4. Mechanical - contact type

All of the measuring transducers mentioned so far produce an analog signal. There are circumstances where the desired output might be total miles of wind passage instead of a time plot of wind speed. Under these circumstances, a mechanical-contact transducer is used.

In this type of transducer, the anemometer shaft is connected through one or more gears to a cam or similar device that opens or closes a contact after the passage of a predetermined amount of air. This contact closure can operate a readout device such as an event marker pen on a recorder. Recorders, such as the one shown in Figure 4, can be furnished with circuitry to provide a pen actuation for each 10, 100 or 1000 contact closures in the transducer. If the average wind speed is desired instead of length of wind passage, the number of contact closures are determined for a given time increment and, knowing the miles or meters of wind passage for each contact closure, the average wind speed over the given time increment is easily determined.



Figure 4.
Event marker recorder

B. Wind Direction

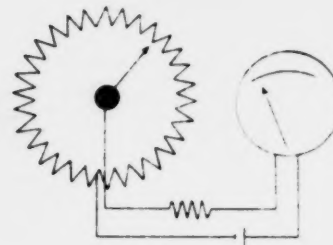
The measurement of wind direction consists of converting the angular position of the wind vane to an energy form that can be transmitted easily. The system of Figure 1h has direct readout obtainable simply by observing the sensor. This system is, at best, very crude.

More advanced wind direction systems usually employ one of 3 types of measuring transducers.

- 1) Potentiometer system
- 2) Synchro-motor system
- 3) Commutator system

1. Potentiometer System

The most common and inexpensive way of converting the angular position of the vane to an electrical signal is through the use of a potentiometer system such as the one shown:



In this system, the shaft of the vane is attached to the wiper arm of the potentiometer. The swinging vane therefore produces a continuously varying voltage that can be recorded on a recording voltmeter or dial indicator. With proper calibration, the recorded voltage gives a direct reading of the angular position of the vane.

The biggest drawback to this system is the unavoidable discontinuity in the potentiometer.

If the wind direction is oscillating about a direction corresponding to this gap (usually north), the voltage output will oscillate between the maximum and minimum value producing what is commonly called "chart painting". With the recorder pen swinging from one end of the chart to the other, the record produced is, at best, very confusing.

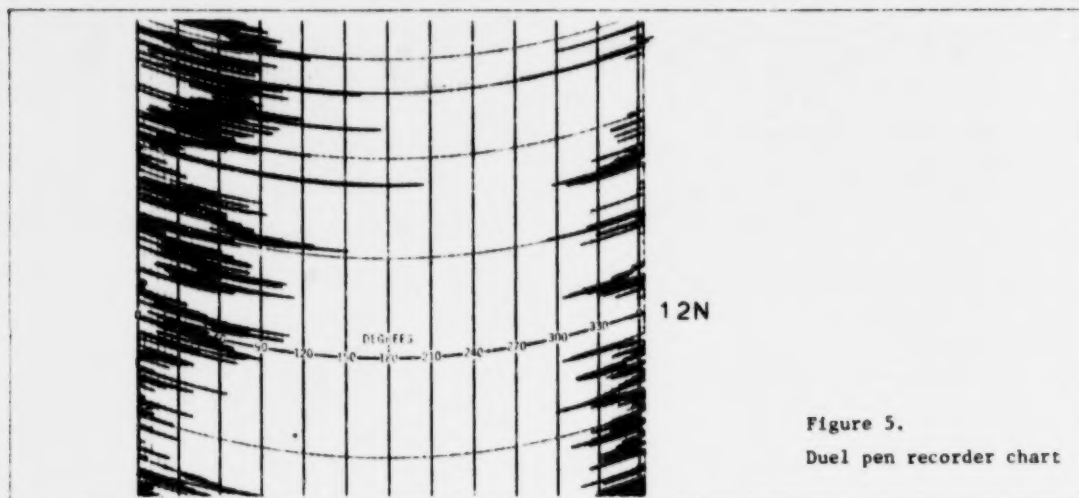


Figure 5.
Duel pen recorder chart

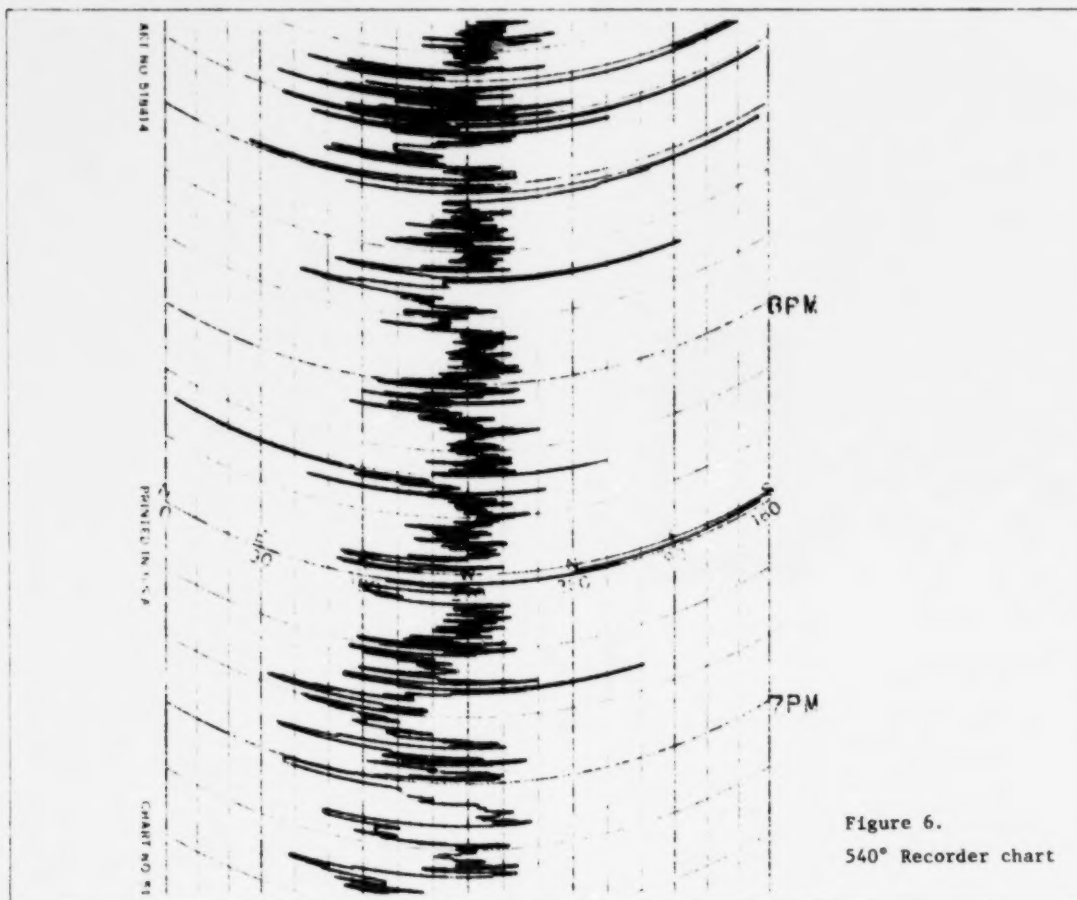


Figure 6.
540° Recorder chart

There are some types of recorder pen movements available that circumvent this problem. Double contact potentiometers with dual pen recorders produce a trace along each edge of the chart when the wind direction corresponds to the gap. Figure 5. illustrates a chart record of this type. In newer recorders, there is available electronic circuitry and a 540° chart that can keep the pen trace in the central portion of the chart. Figure 6. illustrates a chart record of this type.

Wire potentiometers present a problem of excessive wear produced as the contact moves along the wires. The life expectancy of wire-wound potentiometers is only about 6 months - 1 year under continuous operation. Recent advances in this area have produced a conductive plastic potentiometer.

The life expectancy of these potentiometers is about 50×10^6 oscillations which is about 3-5 years under continuous operation. The linearity of these devices is about .5%.

The use of micro-potentiometers produces the lowest movement of inertia of any of the direction transducers available today. This fact has led to their widespread use in the sensitive wind vanes that are noted for their good dynamic performance.

2. Synchro-motor system

This transducer system consists of two synchronous motors wired as shown in Figure 7.

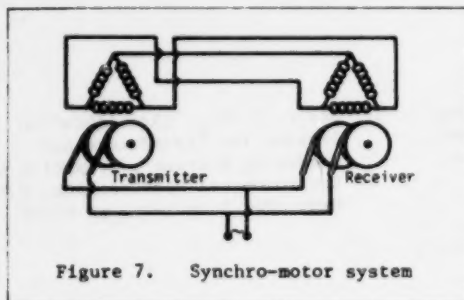


Figure 7. Synchro-motor system

They are commonly known as "Autosyn", "Selsyn" or "Synchrotie" systems.

In this mode, any movement by the shaft of the transmitter will be duplicated by the shaft of the receiver motor usually to an accuracy of about 2°, provided the lead resistance is kept to a maximum of 20Ω.

The vane shaft is coupled to the shaft of the transmitter motor and the shaft of the receiver motor is coupled to a recorder pen or some other read-out indicator. Therefore, any vane movement is duplicated by a movement of the dial needle, recorder pen etc., and with proper calibration and alignment, a direct indication of wind direction is obtained. There is no discontinuity in the movement as with the potentiometer. This transducer system is usually coupled with a 540° chart recorder system to produce an analog trace of wind direction. The system also lends itself readily to a dial indicator display.

The only disadvantage of this transducer system is the relatively large moment of inertia of the motor assembly. This produces a poorer dynamic performance than the micropotentiometer system and limits their use to the more rugged vane types such as the aerovane sensors of Figure 1 m, n.

3. Commutator system

The wind direction transducers discussed so far produce an analog signal that can be converted to an analog chart trace. The commutator transducer system shown in Figure 8. produces contact closures which can be used to activate lights, even marker pens etc.

In this system, the vane shaft is coupled to a unit that has two brush type contacts (A and B) spaced 22 1/2 degrees apart. These brushes make contact with one or two of the 8 conducting sectors (C) that are spaced 45° apart and correspond to 45° of wind direction. When both brushes contact the same sector the direction indicated is one of the 8 compass points, eg. N, NE, E. If the brushes are contacting two of the sectors the indicated direction corresponds to an intermediate direction, such as NNE, ENE, ESE, etc. Therefore, direction indication to 16 points can be obtained with this system.

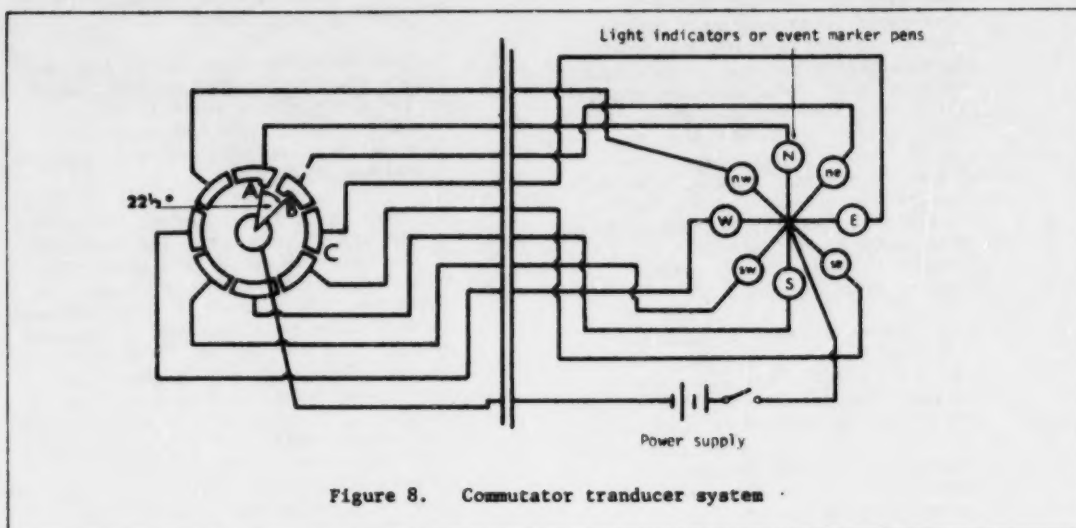


Figure 8. Commutator transducer system

Figure 9 (on opposite page) shows a visual display utilizing lights. An intermediate direction would be indicated by the activation of two adjacent lights.

Figure 10 (opposite page) illustrates a chart record produced by this type of transducer system. An intermediate direction would

be indicated by the activation of two adjacent pens.

The friction inherent in the commutator transducer as well as the crude method of display make this transducer most applicable to operations involving only the acquisition of average wind direction.

REFERENCE:

Wind Measuring Transducers

- 1) Slade, D. H., Editor, "Meteorology and Atomic Energy 1968", U.S., AEC, Division of Technical Information, pp 263-264, pp 269-270
- 2) Middleton, W.E.K., and Spilhaus, A. F., "Meteorological Instruments", Toronto, University of Toronto Press, pp 138-139
- 3) Stein, P. K., "Classification Systems for Transducers and Measuring Systems", Symposium on Environmental Measurements, U.S. Dept HEW, July 1964, pp 65-68

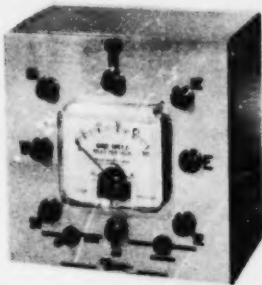
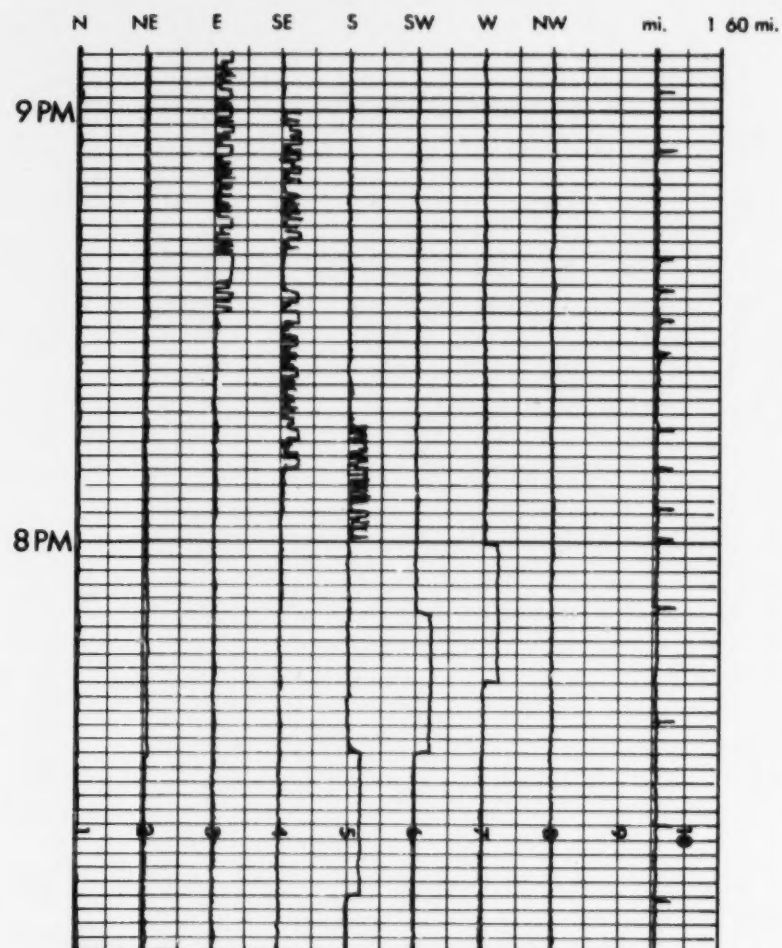


Figure 9.
Commutator system visual display

Figure 10. Commutator system chart record



Measurement of Winds Aloft

Ronald C. Hilfiker

INTRODUCTION

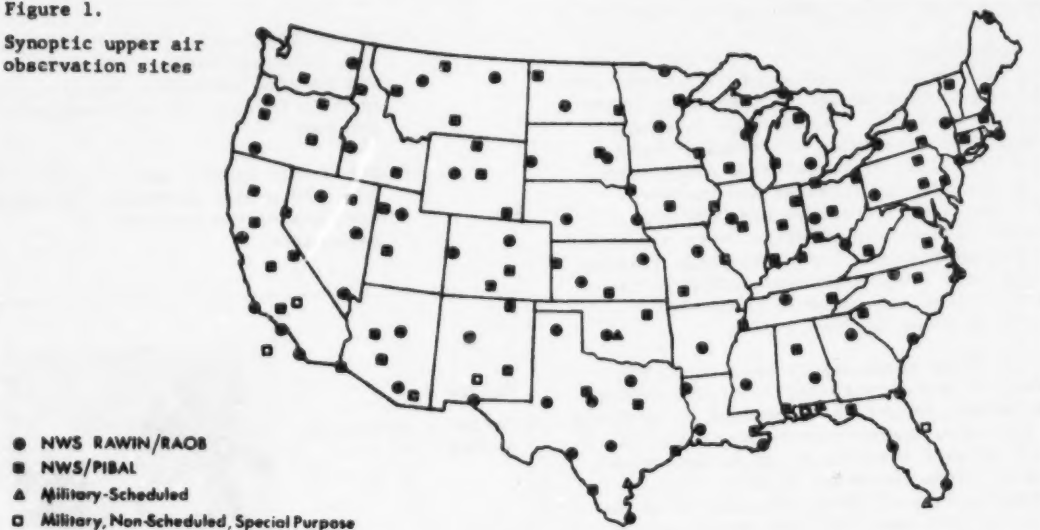
The wind sensors described in the previous sections are limited in application to the measurement of surface wind. In many instances the surface wind will not be representative of the wind at or above plume heights due to the effects of friction, topography, etc. To provide information on the winds aloft (above 300 feet) [90 meters] the National Weather Service maintains a network of upper air sounding stations. Figure 1. shows the location of the stations in this network.

There are two operational methods for obtaining winds aloft data that are in use at these stations:

- 1) Rawinsonde
- 2) Pibal

In addition such methods as constant level balloons, rocket smoke plumes, and wiresondes have been used, mainly in support of research, to obtain winds aloft data.

Figure 1.
Synoptic upper air
observation sites



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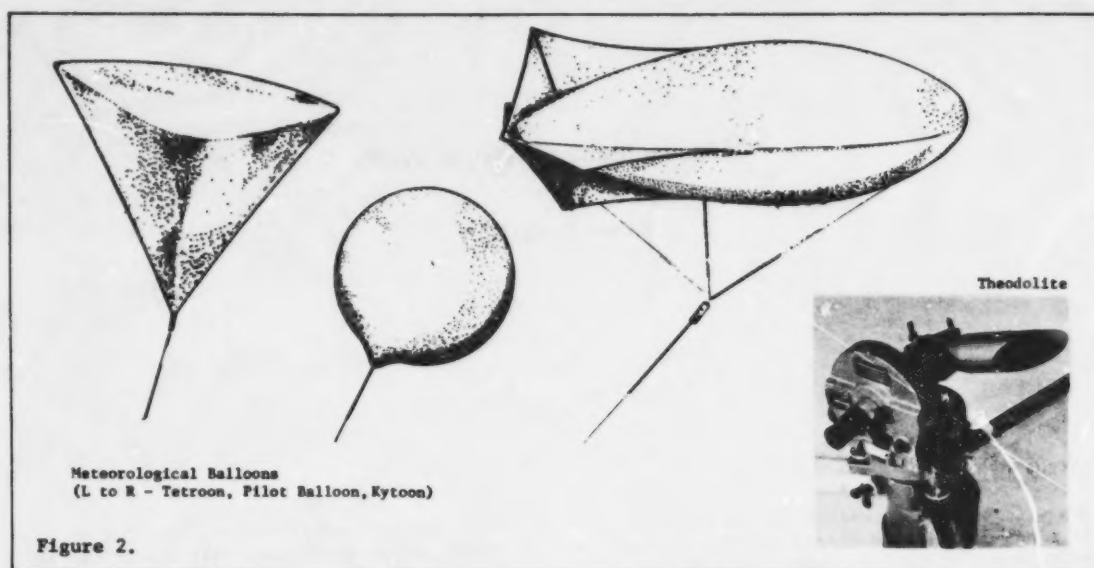


Figure 2.

The 3 types of balloons used in upper air soundings are shown in Figure 2.

RAWINSONDE/RAWIN

About half of the upper air observation stations in the United States employ Radiosonde/Rawin soundings to obtain information on winds aloft. In addition to data on winds, the Rawinsonde transmits data on temperature, pressure and humidity.

The method involves the use of a gas-filled free balloon which carries aloft a resistance wire temperature sensor, a lithium chloride humidity sensor, a bourdon cell pressure sensor, and associated electronics which transmit values of these three parameters to an earth-bound receiver and recorder. Wind data are obtained by tracking this balloon with either radar or radio direction finding apparatus. Radio direction finding is the most frequently used method in the United States. A portable "Radiosonde" system is shown in Figure 3.

The tracking equipment is used to obtain elevation and azimuth angles of the balloon. The balloon height is determined by analysis of the temperature-pressure sounding. If radar is used the height can be determined directly from the radar output. The ascension rate of these balloons is on the order of 1000 feet/min (300 m/min) but is not critical as in Pibal measurements.

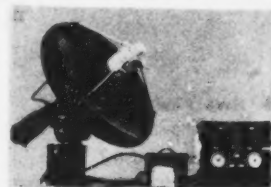
Rawinsonde soundings are made at 12 hour intervals (0000 Z and 1200 Z) at about 70 stations throughout the United States. At about 17 of those stations additional Rawin (wind data only) soundings are made at 0600 Z and 1800 Z.

Rawinsonde soundings have two major drawbacks that limit their use by Air Pollution Control Agencies:

- 1) The sophisticated tracking equipment and personnel needed to run a Rawinsonde, produce a considerable cost in a long term observation program.
- 2) The normal ascent rate of 1000 ft/min (300 m/min) prohibits detailed analysis of the transmitted parameters.

Figure 3.

Portable radiosonde system



PIBAL

In addition to the 70 odd Rawinsonde/Rawin stations, there are about 80 other stations which take wind soundings four times daily (000, 0600, 1200 and 1800 GMT) using only pilot balloons (Pibals). A typical pilot balloon is shown in Figure 2.

The method involves measuring the average wind speed and direction in successive height intervals, and uses a gas-filled free lift balloon which is tracked visually through the use of a theodolite. A theodolite is shown in Figure 2. and is simply an optical system similar to a surveyor's transit that is used to measure the azimuth and elevation angle of the balloon.

Balloon Data:

- Material** - Usually natural rubber. Some balloons have been made out of neoprene.
- Color** - Clear or natural for use with blue sky. Red for use with white cloud overcast. Yellow for use with haze. Black for use at sunrise and sunset.
- Size** - Usually balloons of 30 gram weight are used for normal Pibal ascents to about 30-40 thousand feet (~ 10 KM). Larger balloons with a weight of 100 grams are sometimes used for high ascents because of their greater vertical speed and better visibility at great distances. The 30 g balloon inflates to a diameter of about 2 ft. (.6m) and the 100 g balloon inflates to a diameter of about 3.5 ft. (1.1m).

Procedure:

The preparation for a Pibal Run is somewhat more complicated than the Rawinsonde Procedure since the rate of ascent of the Pibal must be known.

The rate of ascension of a pilot balloon is given by the following equations:

$$30 \text{ g balloon} \quad V = 72 \left(\frac{1}{L} \right)^{.208}$$

$$100 \text{ g balloon} \quad V = 22.7 \left(\frac{1}{L} \right)^{2.52}$$

Where:

- l = Free lift of the balloon.
This is the amount of weight it can hold after inflation and maintain neutral buoyancy.

$$L = \text{Total lift} = l + \text{balloon weight}$$

The results of these formulas are given in table 1., below, for the 30 g and 100 g balloon.

These rates of ascent must be corrected during the first 5 minutes of flight because of the greater density of the air at the lower levels

Min	V (m/min)
1	216
2	198
3	198
4	189
5	189

Table 1.

Balloon Weight	l		V
	Helium	Hydrogen	
30 g	154 g	140 g	180 m/min
100 g	515 g	450 g	280 m/min

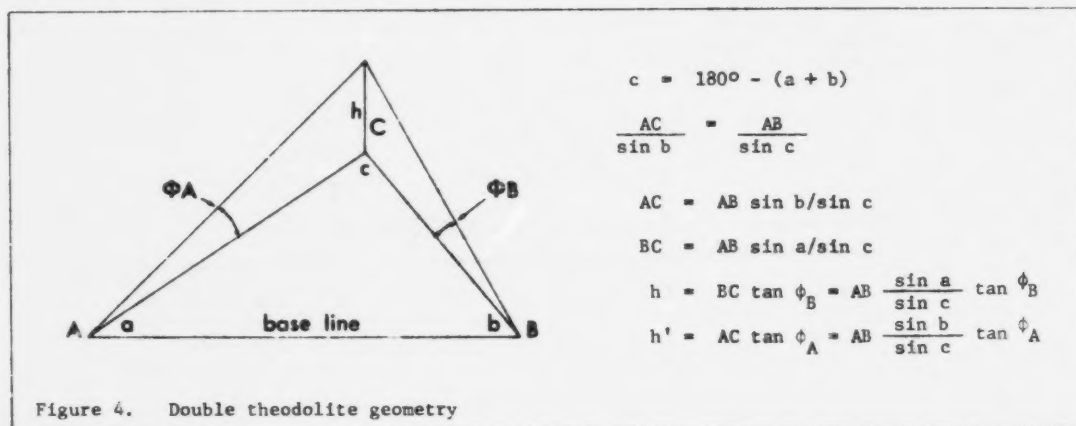
Measurement of Winds Aloft

Normally, elevation and azimuth angles are recorded once per minute through the use of the theodolite. If a detailed sounding is to be made, readings every 30 seconds or less may be required. The height of the balloon is calculated knowing the elapsed time and ascent rate. The downwind distance is then easily calculated by trigonometry knowing the elevation angle and balloon height.

The distance and azimuth can be plotted as a function of time to obtain the wind speed and direction at each minute. A second plot can then be made of wind speed and direction vs. height, and the speed and direction can then be interpolated at 1000 ft. (300 m) intervals which is the final result of a Pibal run.

The above described procedure involves the use of only one theodolite. The basic assumption of a known ascent rate can result in errors in assumed balloon height. If greater accuracy is desired two theodolites can be used, and the height of the balloon determined directly. In this case the ascent rate, as in the Rawinsonde, is not critical.

Because the balloon height is determined from the elevation and azimuth angles of the two theodolites, geometry requires that the distance between the two theodolites (the base line) be known to within the accuracy of the procedure. The base line should be about a mile long and lie in a direction approximately perpendicular to the prevailing wind direction. The balloon height is determined by the geometry of Figure 4.



If the two theodolites are at the same elevation, h will equal h' . The overall accuracy of PIBAL measurements are on the order of ± 1 m/s in speed and $\pm 2^\circ$ in direction. As the height (h) becomes larger, the errors become larger. The above accuracy limits apply to observations below about 15000 ft. (5 KM).

TETROON

A tetroon is a super-pressured constant-level tetrahedron balloon. This balloon, shown in Figure 2, has been designed to float at a constant density level. A tetroon is made of an inelastic material such as Mylar and inflated to about 1 m^3 with a lighter-than air gas mixture at a pressure considerably above that at the computed flight altitude (a super-pressure of about 100 MB). Since the balloon is inelastic, the buoyancy force will remain relatively constant subjecting the balloon only to forces related to density changes and the three-dimensional wind field.

These balloons have found their greatest use in the study of wind flow in the vicinity of cities. The balloons are tracked usually by one of 3 methods.

- 1) Double theodolite
- 2) Radar
- 3) Radio direction finding equipment

TETHERED BALLOON

A tethered balloon system is used to take what is called a wiresonde. A typical wiresonde balloon is shown in Figure 5. In this type of sounding, a balloon is attached to a ground station by a cable which anchors the balloon and also carries signals generated by sensors attached to the balloon. The balloon is raised and lowered by the cable enabling values of wind, temperature, etc. to be sensed at different heights.

This method is not used to any great extent in practice because the technique is cumbersome and can be hazardous during high winds or periods of electrical activity in the atmosphere. There is also the ever-present danger of the build-up of static electricity on the balloon and therefore special grounding procedures must be observed.

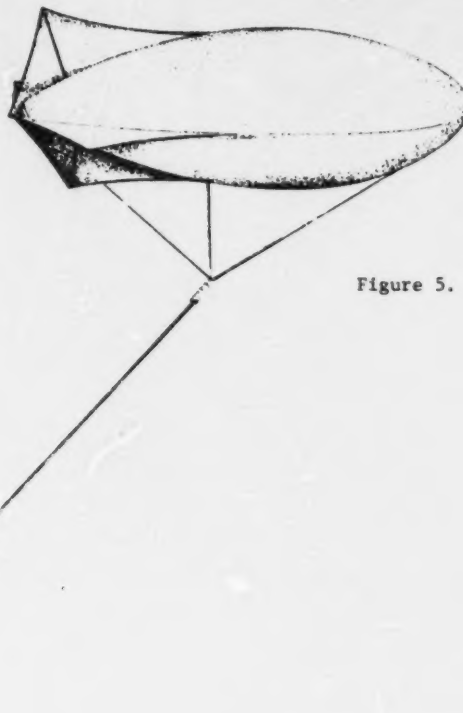


Figure 5.

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Measurements of Winds Aloft:

- 1) "Aviation Weather", Department of Commerce - Federal Aviation Agency Publication, Washington, D. C. 1965
- 2) Slade, D. H., Editor, "Meteorology and Atomic Energy 1968", U.S. AEC, Division of Technical Information pp 298-300
- 3) Middleton, W. E. K., and Spilhaus, A. F., "Meteorological Instruments", Toronto, University of Toronto Press 1953 pp 166-196

Section Three

DYNAMIC RESPONSE OF METEOROLOGICAL SENSORS AND RECORDERS

Principles of Dynamic Response

Introduction

Dynamic Response of Sensors

Dynamic Response of Indicating Meters and Recorders

Dynamic Response of Sensors Plus Recorders

Appendices

Equipment and Techniques to Obtain the Time Constants of Temperature Sensors

Equipment and Techniques to Obtain the Distance Constants of Anemometers

Cosine Response of a Helicon

Equipment and Techniques to Obtain the Damping Ratios and Damped Natural Wave Lengths of Wind Vanes

Sensor Specifications for Wind Instruments

Principles of Dynamic Response

Gerald C. Gill

Introduction

One area in the field of micrometeorology that has been largely overlooked by many research personnel is how fast the meteorological sensor responds to the parameter it is supposed to be measuring. Also, how accurately does the sensor and recorder combination record the true fluctuations of the meteorological variable?

Examples:

1. Suppose you have been asked to make a spot check on the accuracy of a dry bulb thermometer in an instrument shelter. Suppose the thermometer was reading a steady $+30.5^{\circ}\text{F}$ and the wind was blowing through the shelter at 5 mph. You have been supplied with a good mercury-in-glass thermometer whose calibration is known within $\pm 0.1^{\circ}\text{F}$. You step out of the heated office (70°F) and place the bulb of the standard thermometer adjacent to the bulb of the thermometer being tested. How long should you wait before reading the two thermometers in order to know the standard thermometer has come within 0.2°F of the true air temperature—1 min? 3 min? 10 min?

2. On another occasion you are using this same standard thermometer to check the readings of a remote sensing resistance thermometer. The wind was averaging 5 mph and you read the thermometer at 15-sec intervals. After plotting a 10-min series of readings you found that three sinusoidal fluctuations in temperature of average period 3 min was recorded, and the amplitude of the temperature fluctuation was approximately $\pm 1.0^{\circ}\text{F}$ from the running mean. Approximately how many degrees did the actual air temperature fluctuate— $\pm 1^{\circ}\text{F}$? $\pm 2^{\circ}\text{F}$? $\pm 4^{\circ}\text{F}$? $\pm 8^{\circ}\text{F}$?

The answer to both of these questions depends on the response of the standard thermometer which, in turn, can be defined by a single number, the Time Constant. If the time constant of the standard thermometer was 100 sec when in air traveling at 5 mph, it would be necessary to wait 530 sec (nearly 9 min) before the standard thermometer placed in the shelter cooled to within 0.2°F of the true air temperature (from Table 1, for 99.5% recovery).

In the second example, the thermometer was cycling $\pm 1.0^{\circ}\text{F}$ from the mean every 3 min.

Knowing the time constant of the bulb ($T = 100$ sec) and the period of the cycle ($P = 180$ sec) the actual air temperature fluctuations must have been approximately $\pm 3.5^{\circ}\text{F}$ (Figure 3, when $T/P = .56$, $x/x_0 \sim 3.5$).

3. Suppose you have been supplied with a wind vane whose static calibration curve shows it to be accurate with $\pm 2^{\circ}$ for the complete 360° of azimuth and you are asked to specify its accuracy of recording wind direction fluctuations for all frequencies up to one gust per second. How could you do this? By obtaining its response curve in a wind tunnel (Figure 7) one can determine its damped natural frequency, its damping ratio and its approximate dynamic response to gusts of all wave lengths.

To assist you in determining the dynamic response of some of your sensors two of the simpler force equations are analyzed and a set of curves provided which will permit adequate solutions to a surprisingly large proportion of problems.

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Dynamic Response of Sensors

I. Sensors with First Order Response (Equation of Forces Being a First Order Differential Equation)

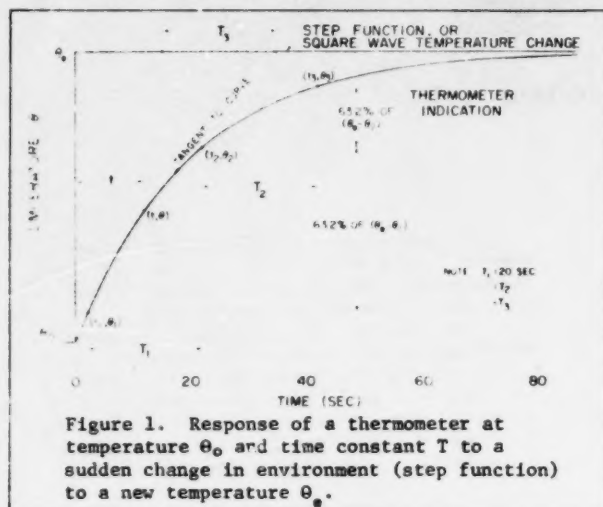


Figure 1. Response of a thermometer at temperature Θ_0 and time constant T to a sudden change in environment (step function) to a new temperature Θ_e .

Consider a thermometer, initially at a temperature Θ_0 , which is suddenly transferred into a moving air stream whose temperature is Θ_e (see Figure 1). Experiment shows that the indicating thermometer will approach the new temperature Θ_e asymptotically at a rate depending on the temperature difference $\Theta_e - \Theta_0$. This may be expressed by the equation:

$$\frac{d\Theta}{dt} = \frac{\Theta_e - \Theta}{\lambda} \quad (1)$$

(a first order differential equation)

where

Θ = instantaneous indication of thermal bulb at time t

Θ_e = temperature of new environment (assumed constant)

Θ_0 = initial temperature of thermometer

t = elapsed time (sec) after thermometer immersed in new environment

λ = constant, depending on shape of thermometer bulb, the thermometer liquid used, and on properties of the new environment. (Note that λ has the dimensions of time in the equation.)

Solving this differential equation we get:

$$(\Theta_e - \Theta) = (\Theta_e - \Theta_0) e^{-t/\lambda} \quad (2)$$

Now when time $t = \lambda$,

$$\begin{aligned} (\Theta_e - \Theta) &= (\Theta_e - \Theta_0) e^{-\lambda/\lambda} \\ &= (\Theta_e - \Theta_0) e^{-1} \\ &= \frac{\Theta_e - \Theta_0}{2.718} \\ &= .368(\Theta_e - \Theta_0) \end{aligned} \quad (3)$$

that is, after the elapse of λ sec the instantaneous difference in temperature $(\Theta_e - \Theta)$ has been reduced to 36.8% of its original value, or, in time λ the thermometer will have responded to 63.2% of the initial temperature difference.

This constant λ having the dimensions of time is called the time constant T , and corresponds to the elapsed time after a sudden change in the environment temperature for the indicated temperature difference to be reduced to 1/3 of its initial value.

*This portion of the article is largely abstracted from earlier papers by the author, "Data Validation," 1964, Symposium on Environmental Measurements, Data Validation and Logical Interpretation; U.S. Public Health Service Publication No. 999-AP-15, pp. 85-100, and "On the Dynamic Response of Meteorological Sensors and Recorders," Proceedings of the First Canadian Conference on Micrometeorology, Part I, Meteorological Service of Canada, Toronto, Canada, 1967, pp. 1-27.

Table 1.

RECOVERY OF SENSOR WITH FIRST ORDER RESPONSE AFTER A STEP FUNCTION INPUT								
Recovery	50%	63.2%	86.5%	90%	95%	99%	99.5%	99.9%
Elapsed Time	0.7T	1.0T	2.0T	2.3T	3.0T	4.6T	5.3T	6.9T

(A) Response of a first order sensor to square wave (step function) input.
In time T sec the sensor will have responded to 63.2% of the initial temperature difference. In the succeeding T sec the sensor will have responded to 63.2% of the remaining temperature difference, $\{.368 (\theta - \theta_0)\}$, that is, in $2T$ sec it will have responded to 86.5% $\{1 - .368^2\} \times 100\%$ of the initial temperature difference. Table I relates percentage response of the sensor to other values of elapsed time-measured in terms of the time constant.

In determining the time constant T by the method given above, other points on the curve beside θ_1 may be used. For instance, T_1 = elapsed time after t_1 for temperature indication to reach θ_2 , where θ_2 is determined by equation $(\theta_2 - \theta_1) = .368 (\theta_1 - \theta_0)$. T may also be determined by drawing a tangent line to the curve and noting elapsed time T_3 where it cuts line θ_2 (Figure 1).

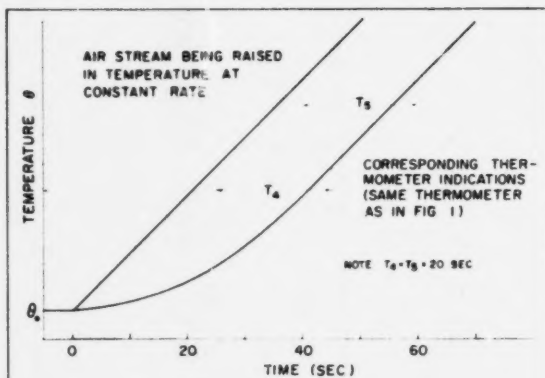


Figure 2. Response of a thermometer (with time constant T) that is exposed in an air stream that is suddenly heated at a constant rate.

The unique value of the term "time constant" is shown in Figure 2, which illustrates what happens when the same thermojunction sensor has been immersed in an air stream at the same speed as before and at constant temperature θ_0 , when at time $t = 0$ the temperature is raised at a constant rate. The temperature sensor does not immediately respond to this constant rate of temperature rise but takes about 40 sec to reach this rate. The time constant T is the lag time T_4 or T_5 .

For a given air speed (or water speed) and a given temperature sensor the time constants T_1 , T_2 , T_3 , T_4 , and T_5 should all be the same (within a few percent).

Note: (1) The time constant for a thermometer exposed in an air stream at a certain speed is about 60 times as great as it is for the same thermometer exposed in a water stream at the same speed.

(2) Figure 1 is the response curve of a "single capacity system," such as a bare resistance wire, or a bare thermojunction, and very close to the curve of a "two capacity system" such as a mercury-in-glass thermometer. But the initial response to the sudden temperature change is more sluggish for a "multiple capacity system" (such as a resistance thermometer inserted into a protective metal tube) and the initial part of the response curve (near $t = 0$) is curved rather than abrupt. An approximate time constant for such a sensor may be obtained by choosing the point t_1 , θ_1 sufficiently along the plotted curve that this initial transitional response of the sensor is not utilized (see Equation (6)).

(B) Response of a first-order sensor to a sinusoidally fluctuating input. The accuracy of indications of the amplitude of a sinusoidally fluctuating input is given by the following equations:

(1) Amplitude ratio for a single-capacity system (e.g., bare resistance wire, or butt-weld thermojunction):

$$\frac{x}{x_o} = \frac{1}{\sqrt{1 + (\omega T)^2}} \quad (4)$$

or

$$\frac{T}{P} = \frac{\sqrt{(x_o/x)^2 - 1}}{2\pi} \quad (5)$$

(2) Amplitude ratio for a multiple-capacity system (bulb in well):

$$\frac{x}{x_o} = \frac{1}{\sqrt{1 + (\omega T_1)^2} \sqrt{1 + (\omega T_2)^2}} \quad (6)$$

where

x = indicated amplitude of temperature fluctuation

x_o = actual amplitude of temperature fluctuation

ω = angular velocity (rad/sec) = $2\pi f = 2\pi/P$

f = frequency of fluctuation

P = period of fluctuation = $1/f$

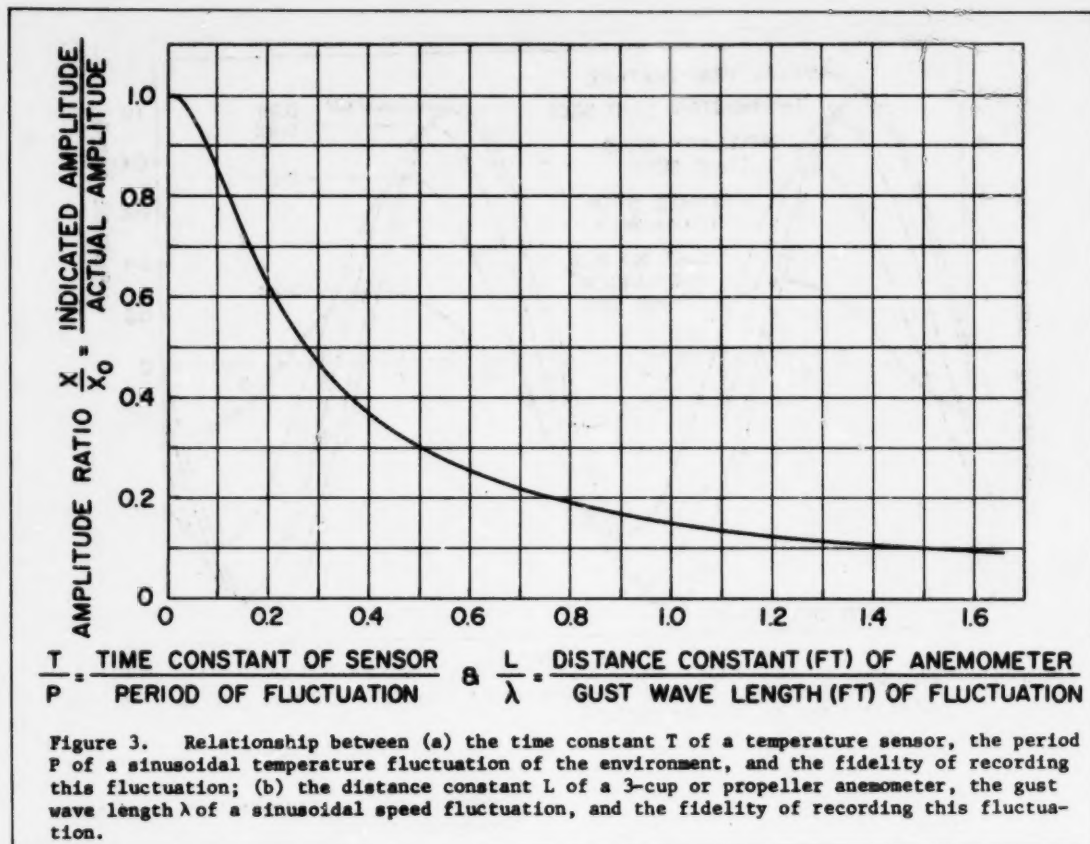
T = time constant

T_1 and T_2 are time constants of bulb alone and well alone.

Table 2 was computed from Equation (5), and Figure 3 is a graphic representation of Table II and Equation (5), relating the time constant T and the period P of the cycle to the amplitude ratio x/x_o of the sensor.

Table 2.

RESPONSE OF A TEMPERATURE SENSOR OF TIME CONSTANT T TO A SINUSOIDALLY FLUCTUATING TEMPERATURE OF PERIOD P , AND RESPONSE OF AN ANEMOMETER OF DISTANCE CONSTANT L TO A SINUSOIDALLY FLUCTUATING WIND SPEED OF GUST WAVE LENGTH λ	
Amplitude Ratio, x/x_o	Corresponding Ratio of: <u>Time Constant T</u> Period of cycle P or <u>Distance Constant L</u> Gust Wave Length λ
.99	.016
.98	.032
.96	.046
.94	.059
.92	.068
.90	.078
.86	.095
.82	.112
.78	.128
.74	.144
.70	.162
.65	.186
.60	.211
.55	.242
.50	.275
.40	.363
.30	.505
.20	.78
.15	1.04
.10	1.58
.05	3.19



(Example: Suppose the time constant of a thermometer in a wind of 10 mph were 100 sec ($T = 100$ sec) and that sinusoidal air temperature fluctuations of $+5^\circ\text{F}$ were occurring at 5-min periods ($P = 300$ sec). The ratio $T/P = 100/300 = 0.33$. From the graph the amplitude ratio would be 0.43. The sensor would show 43% of the true temperature fluctuation. Thus by knowing the time constant of the sensor and the period of the fluctuations, we can quickly specify the fidelity response of the temperature sensor. If we want the temperature sensor to respond to 90% of the temperature fluctuations, the ratio T/P must be .075 or less; that is, the time con-

stant of the sensor could not be more than 7.5% of the shortest period of fluctuations the sensor is to follow.)

Figure 4 illustrates the response of several average temperature sensors to a sinusoidally fluctuating air temperature having a period of 300 sec.* The effects of time constant on amplitude ratio and phase shift are clearly demonstrated.

The following formula (experimentally determined) relates the diameter of cylindrical metal temperature sensors, the air flow rate, and the time constant:

*Courtesy of E.W. Jensen and K.C. Kiesling, Eastman Kodak Co., "Response of Thermal Bulbs," I.S.A. Instrument Maintenance Clinic, Buffalo, New York, Sept. 15-17, 1950.

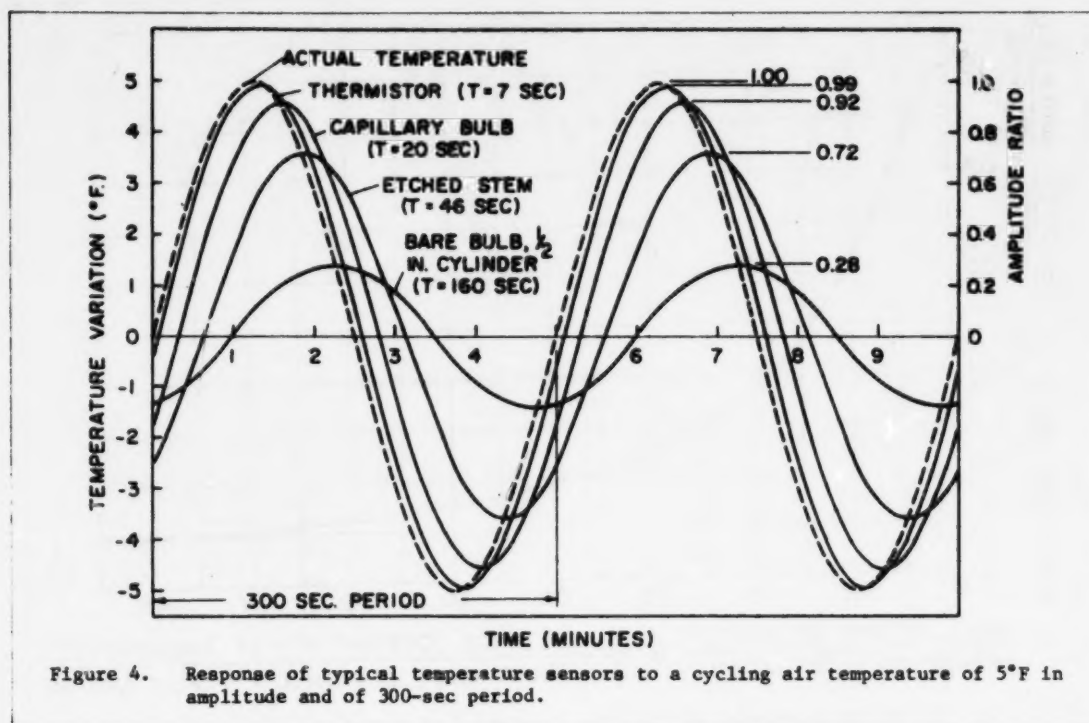


Figure 4. Response of typical temperature sensors to a cycling air temperature of 5°F in amplitude and of 300-sec period.

$$T \approx 6000 d^{1.34} v^{-0.40} \quad (7)$$

where

T = time constant (sec)

d = diameter of cylinder (in.)

v = air speed (ft/min)

Note that the time constant is roughly inversely proportional to the square root of the wind speed.

Some laboratory and field methods of measuring the time constants of temperature sensors is given in Appendix A.

(C) Sensors with first-order response. Essentially all temperature-sensing instruments have first-order response, e.g., mercury-in-glass

thermometers, gas thermometers, resistance thermometers, etc.

Many flow-measuring sensors have first-order response, e.g., cup, propellor, and hot wire anemometers; cup and propellor water-speed-measuring sensors and turbine types of sensors.

Note: (3) A first-order sensor never indicates a larger change in the measured variable than the true change, even with a step-function input.

(D) Response of anemometers. To obtain the dynamic response of a propellor anemometer (or 3-cup anemometer) we use the system developed by Schubauer and Adams.* The anemometer is placed in a wind tunnel, and the tunnel speed adjusted to a steady value, say 15 ft/sec. The anemometer is kept from turning, and suddenly released at

*G.B. Schubauer and G.H. Adams, "Lag of Anemometers," Nat. Bur. Stand. Rpt. #3245, April 1954, 16 pages, 14 figures.

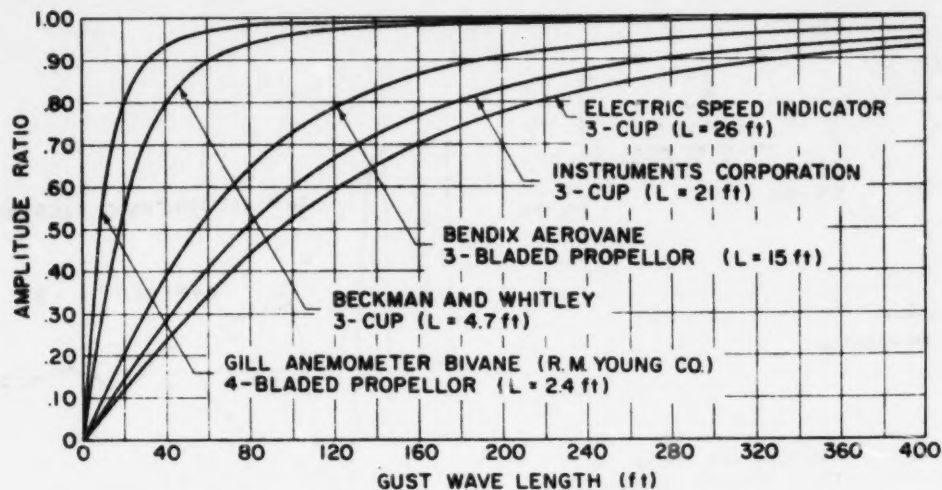


Figure 5. Response to several typical wind speed sensors to sinusoidal wind speed fluctuations of varying gust wave length.

time $t = 0$. A curve similar to Figure 1 relating rate of turning versus time is obtained. Suppose that the time constant is found to be 1.0 sec (typical of Bendix Aerovane 3-bladed propellor). Now suppose we increase the tunnel speed to 30 ft/sec. We find the time constant to be reduced to 0.5 sec. If the tunnel speed is increased to 60 ft/sec the time constant is found to be approximately 0.25 sec. In such cases the term "distance constant" is more approximate and this is the length of air column that passes after the release of the propeller for it to reach 63% of its terminal velocity. In this case the Distance Constant $L = 15$ ft (1.0×15 or 0.5×30). The curve of Figure 3 is still valid but Equation (5) transforms to:

$$\frac{L}{\lambda} = \frac{\sqrt{(x_0/x)^2 - 1}}{2\pi} \quad (8)$$

where

L = distance constant (ft)

λ = wave length of sinusoidal speed fluctuation, or gust wave length (ft)

x_0 = actual amplitude of speed change

x = indicated amplitude of speed change

When the distance constant L for a particular anemometer has been determined the fidelity of recording gusts of various wave lengths may be determined by use of Equation (8) (or Table II), and the results plotted as in Figure 5. In this figure the dynamic responses of several commercially available wind speed sensors to sinusoidal wind speed fluctuations have been plotted.

A field method of obtaining the approximate distance constants of anemometers is given in Appendix B.

II. Sensors With Second-Order Response (Equation of Forces Being a Second-Order Differential Equation)

(A) Response of a second-order sensor to a square-wave (step function) input. In the electric circuit of Figure 6 after switch S has been closed for some time the galvanometer reading G will have become steady at some value, say, $A \cos \delta$ divisions. If at time $t = 0$ switch S is opened, the galvanometer coil will quickly start turning toward its zero position; overshoot this value by maybe 60%; reverse direction; and again overshoot, executing a simple harmonic oscillation of decreasing amplitude, as shown in Figure 7. (Here the sensor does indicate a larger change than the true change—larger by a factor of 60%—thus differing markedly from

Dynamic Response of Sensors

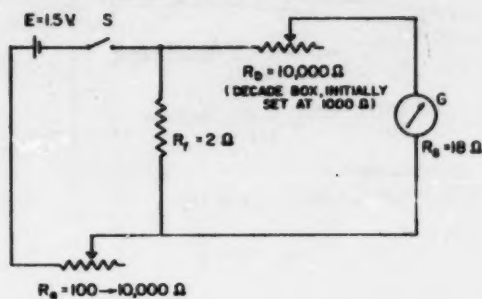


Figure 6. An electric circuit to determine the critical damping resistance of a galvanometer or indicating meter.

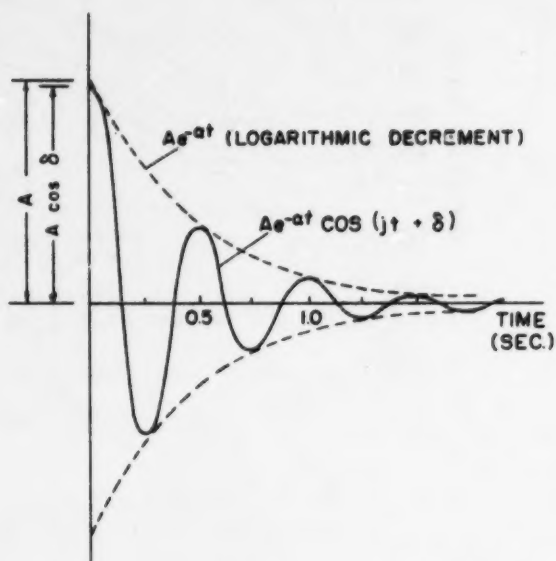


Figure 7. Typical galvanometer decay curve ($h = 0.16$).

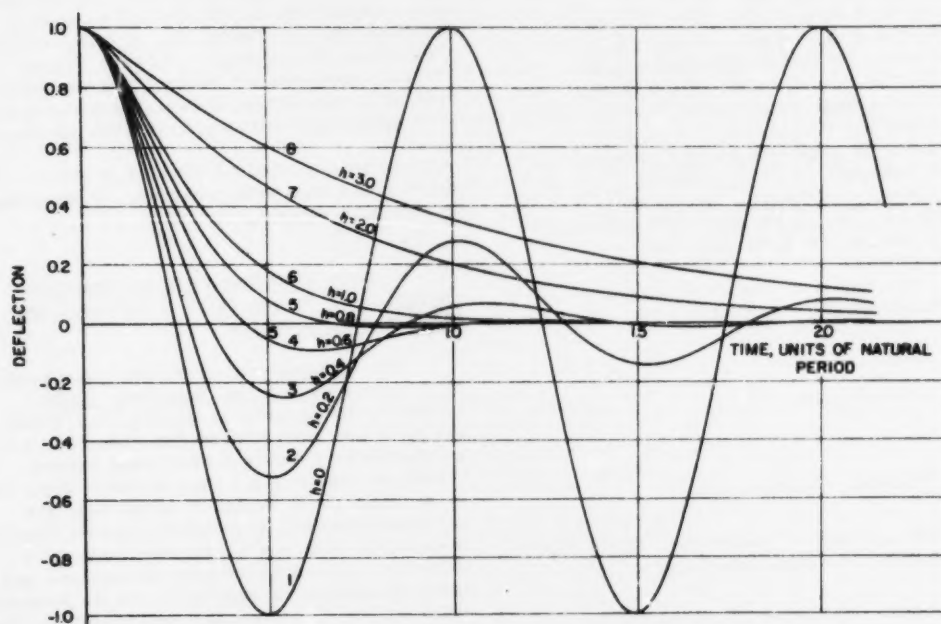


Figure 8. Damped oscillations—galvanometer decay curves for damping ratios of $h = 0.0$ to $h = 3.0$.

sensors with first-order response.) The equation of forces is:

$$I \frac{d^2\theta}{dt^2} + C \frac{d\theta}{dt} + K\theta = 0 \quad (9)$$

where I = moment of inertia of the coil suspension system

C = damping constant (primarily self-induced electromagnetic damping; secondarily air damping)

K = spring constant

θ = angular deflection (measured from rest position)

A general solution to this equation (when the decay curve is similar to that of Figure 7) is

$$\theta = Ae^{-\alpha t} \cos(\gamma t + \delta) \quad (10)$$

where $A \cos \delta$ = initial displacement from zero

$$\alpha = C/2I, \beta = \sqrt{K/I}$$

$$\gamma = \sqrt{\beta^2 - \alpha^2}, \cos \delta = \sqrt{1-h^2}$$

h = damping ratio

As mentioned previously, this decay curve, Figure 7, is a simple harmonic motion ($\cos \gamma t$) of decreasing amplitude with envelope defined by the dashed curve $Ae^{-\alpha t}$.

If the electrical resistance R_d were decreased, the damping coefficient would be increased and the decay curve would show fewer oscillations, each of decreased amplitude. For a certain value of ($R_d + R_f$) the instrument deflection returns to zero in a minimum of time without any overshoot. This condition is known as critical damping and is shown in Figure 8 by curve 6, labelled $h = 1.0$. Other values of the damping ratio h from 0.0 to 3.0 are shown in Figure 8.

In the decay curve of Figure 7, the galvanometer has a damping ratio $h = 0.16$, and a damped frequency of 2 cps (damped period $t_d = 0.5$ sec). In the circuit of Figure 6 with $R_d = 1000$ ohms, if a sinusoidal voltage of constant amplitude but of varying

frequency were applied across resistance R_f , the galvanometer would swing back and forth at the same frequency as the input signal; when the input frequency approached 2.0 cps, the galvanometer would resonate and show amplitude fluctuations up to 3.0 times the true amplitude! Thus the dynamic response of the sensor can greatly distort the true form of the input signal.

Figure 8 shows the decay curves of a galvanometer whose damping ratio h has been varied in steps from $h = 0.0$ to $h = 3.0$. Where $h = 0.0$ the galvanometer would execute simple harmonic motion without decreasing amplitude indefinitely. (This would represent a frictionless galvanometer without electrical or air damping, a theoretical case.) Time is given in units of the natural period (t_n) of the galvanometer. Note that as the damping ratio increases the "damped period" t_d increases. The relationship between the "damped period" and the damping ratio is given by:

$$t_n = t_d \sqrt{1-h^2} \quad (11)$$

or

$$f_n = f_d \sqrt{1-h^2} \quad (11^1)$$

where t_n = natural period of oscillation of galvanometer

f_n = natural frequency of oscillation of galvanometer

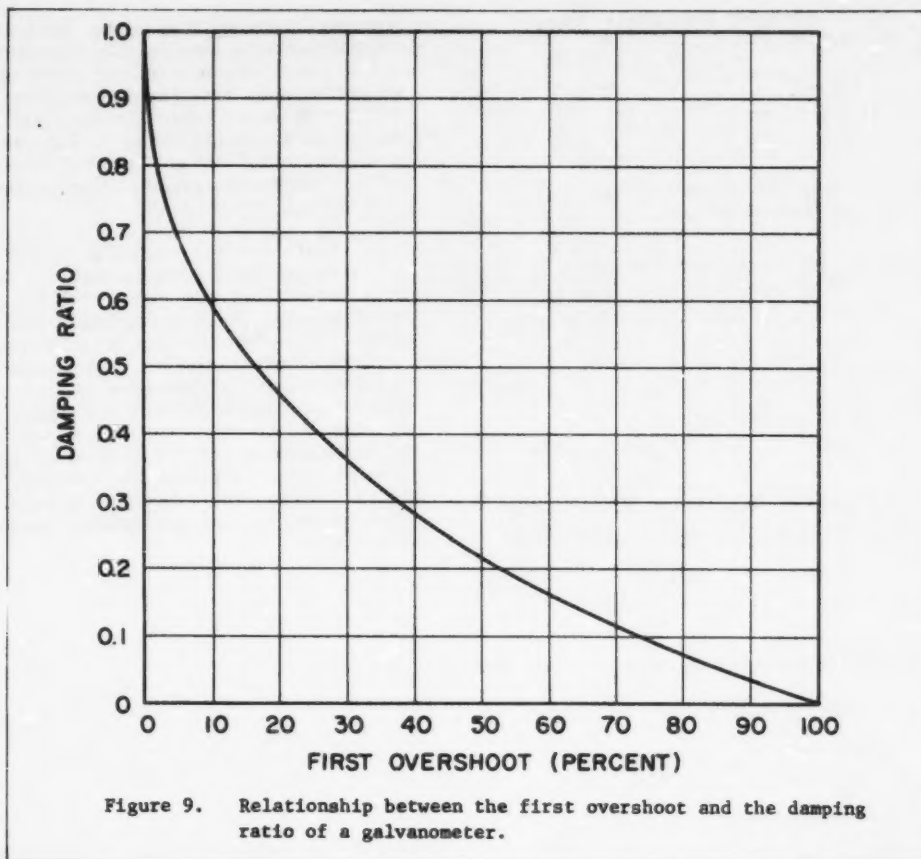
t_d = damped period

h = damping ratio

Note that for $h = 0.2$ the first overshoot $\sim 52\%$ of the initial displacement; the second overshoot $\sim 52\%$ of first overshoot, etc.

The damping ratio can be determined from the decay curve of the sensor by the use of the following equation:

$$h = \frac{\log_{10} A_o/A_n}{\sqrt{1.862 n^2 + (\log_{10} A_o/A_n)^2}} \quad (12)$$



in which A_0 is the first considered amplitude or displacement measured from the rest position and A_n is the amplitude on the n th succeeding swing past the rest position.

As an alternative to solving this equation for each test, Figure 9 relates the damping ratio h with the first overshoot after release, (that is, in Equation (12) A_0 = initial displacement; A_1 = first overshoot; $n = 1$). (Example: In Figure 8, curve 2, the first overshoot is approximately 52 1/2%. Referring to Figure 9, with an abscissa of 52 1/2%. Referring to Figure 9, with an abscissa of 52 1/2%, the damping factor $h = 0.20$, which agrees with the value of h given for curve 2, Figure 8.)

(B) Response of a second-order sensor to a sinusoidally fluctuating input. In most applications we are not concerned primarily with the response of the sensor to step-function (square-wave) inputs, but rather

with its response to sine-wave inputs.

Figure 10 shows the dynamic response of sensors with damping ratios from $h = 0.1$ to $h = 1.0$ to sine-wave inputs. This graph shows that for a galvanometer, with a damping ratio of 0.2, if a signal of several cycles of frequency f_1 such that f_1 were 0.5 that of the natural frequency f_n of the galvanometer (that is, $f_1/f_n = 0.5$), the galvanometer would indicate sinusoidal fluctuations 1.25 times that of true; when $f_1/f_n = 0.95$, the galvanometer would show fluctuations up to 2.50 times that of true (amplitude ratio = 2.50); and at $f_1/f_n = 2.0$, the amplitude ratio would be only 0.32, or 1/3 that of true. Thus for a galvanometer having a damping ratio of 0.2 for good fidelity in indicating, the ratio f_1/f_n 0.2, or, the impressed frequency should never exceed 20% of the natural frequency of the galvanometer. This is a serious limitation on the use of the system because often one cannot limit the input frequency. If the

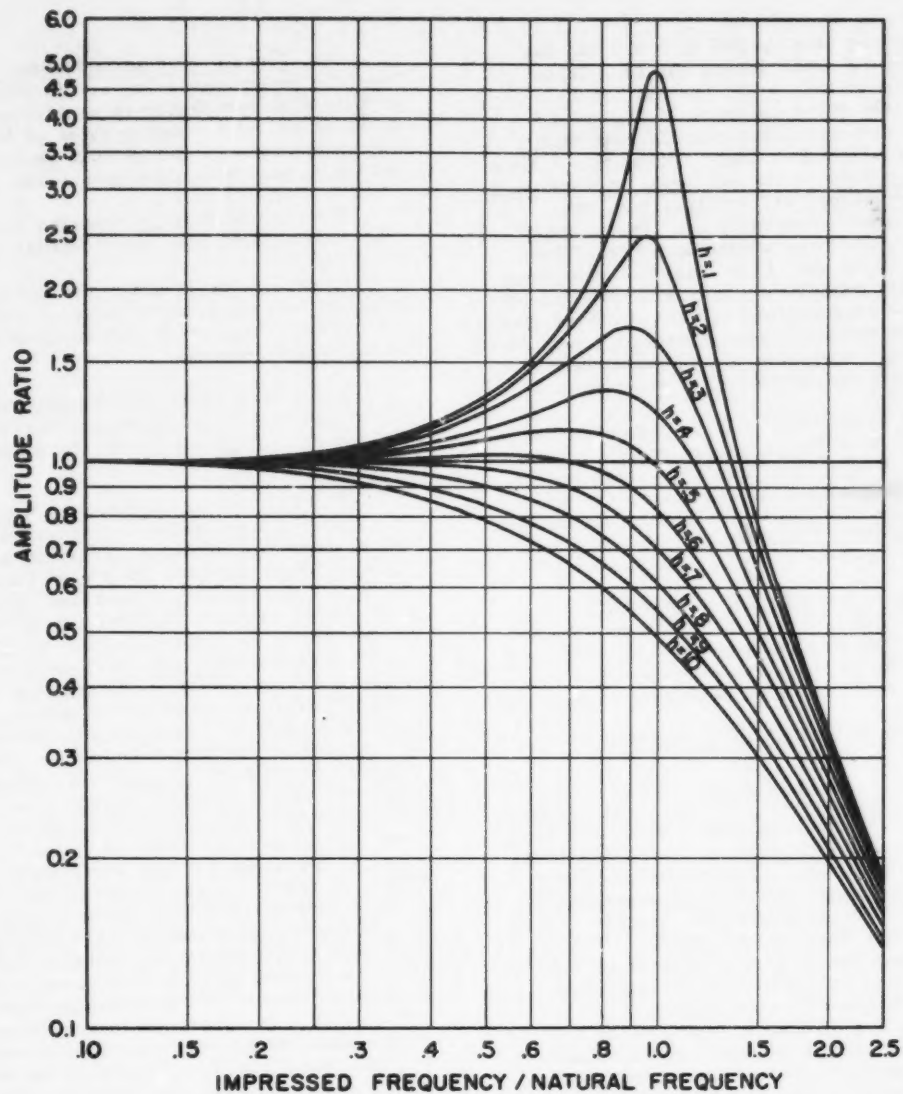


Figure 10. Relationship between the damping ratio of a galvanometer (or voltmeter) and its dynamic response to sinusoidal input voltages of constant amplitude but varying frequency.

galvanometer were damped to $h = 0.64$, the galvanometer would record the true input amplitude (within $\pm 2\%$) for all input frequencies where the ratio $f_i/f_p < 0.6$; and would record input signals less than true for all higher input frequencies. This value $h = 0.64$ is the most desirable damping ratio for almost all applications, and manufacturers generally specify the input circuit resistance needed to achieve this ratio. (Note that if the galvanometer were critically damped, $h = 1.0$, and high-fidelity recording were desired (within $\pm 2\%$ of true), the input frequency should never exceed 15% of the natural frequency of the galvanometer, a very serious limitation on the system.)

Most galvanometers have a damping ratio of 0.2 or less in a high-resistance circuit. This would be true of ammeters, volt-meters, etc., were they not provided with air or electromagnetic damping. Such meters on open circuit usually have values of $h = 0.4$ to 0.7, depending on their intended use.

Thus to specify the accuracy of recording fluctuating input frequencies, one must know the damping ratio of the sensor, its natural frequency, and the range of frequencies of the input signal.

Approximate Method of Adjusting Meter Damping to $h = .64$

The galvanometer response curves shown in Figure 10 were obtained by adjusting the external damping resistance to ten different values (from $h = 0.1$ to $h = 1.0$), and then subjecting the galvanometer to a series of sinusoidal voltage inputs of constant amplitude but varying in frequency from 0.1 to 2.5 times the natural frequency of the galvanometer, and recording the amplitude of the deflection in each case. This consumes a lot of time and employs an instrument not common to most laboratories—a low frequency function generator. There is an approximate way to adjust the galvanometer resistance to provide $h = .64$ for good dynamic response without the use of a low frequency function generator. From Equation (12) or Figure 9 it may be seen that for $h = .64$, the first overshoot following a square wave input should be 7.2% of the initial displacement. By using the electric circuit of Figure 6 one can quickly adjust the external damping resistance to provide this 7.2% overshoot and thus determine the desired external damping resistance for $h = 0.64$.

(C) Sensors with second-order response.

Electric meters generally are in this category. Fortunately, manufacturers usually provide their meters with damping rates of 0.6 or higher or indicate the circuit resistance that should be used to attain this value.

Flow meters that incorporate a tapered tube with a float have second-order response.

Force sensors in which the force is balanced against a spring (either longitudinal extension or angular rotation) usually have second-order response.

In all such cases the dynamic response of the sensor must be known or measured if the accuracy of recording is to be specified.

(D) The dynamic response of wind vanes.

To a first approximation the equation of forces on most wind vanes deflected a few degrees from axial flow in a wind tunnel are those of Equation (9). The decay curve of a typical commercial wind vane when released in the tunnel is similar to that of Figure 7. Then if the vane were subjected to sinusoidal wind direction fluctuation of constant angular amplitude but varying in frequency we might expect to get overshoot of the vane at certain frequencies. We do. Although it is rare to observe in nature true wind direction fluctuations of a particular frequency for more than one complete cycle, the resonance of most wind vanes to gusts can be very strikingly shown. Figure 11 shows the simultaneous recording of wind directions atop a 150-ft tower as shown by a standard commercially available wind vane (Instruments Corporation, * Type M) having a damping ratio $h = .20$, and, a Gill Anemometer Bivane having a damping ratio $h = .60$. The two instruments were mounted at the same height and, separated about 6 ft. horizontally. From Figure 10 we could expect the commercial wind vane to show amplitude fluctuations up to 250% of the true fluctuations ($h = .2$), and the Gill instrument up to 103% of true. Resonance in swinging of the Instruments Corporation vane is apparent, it indicating wind direction fluctuations up to 190% that shown by the Gill instrument even though the latter has a much faster response. Thus the over indication of wind direction fluctuations by a standard commercially available wind vane is demonstrated. Wind vanes of other manufacture are both better and worse than this make, it being an average sensor.

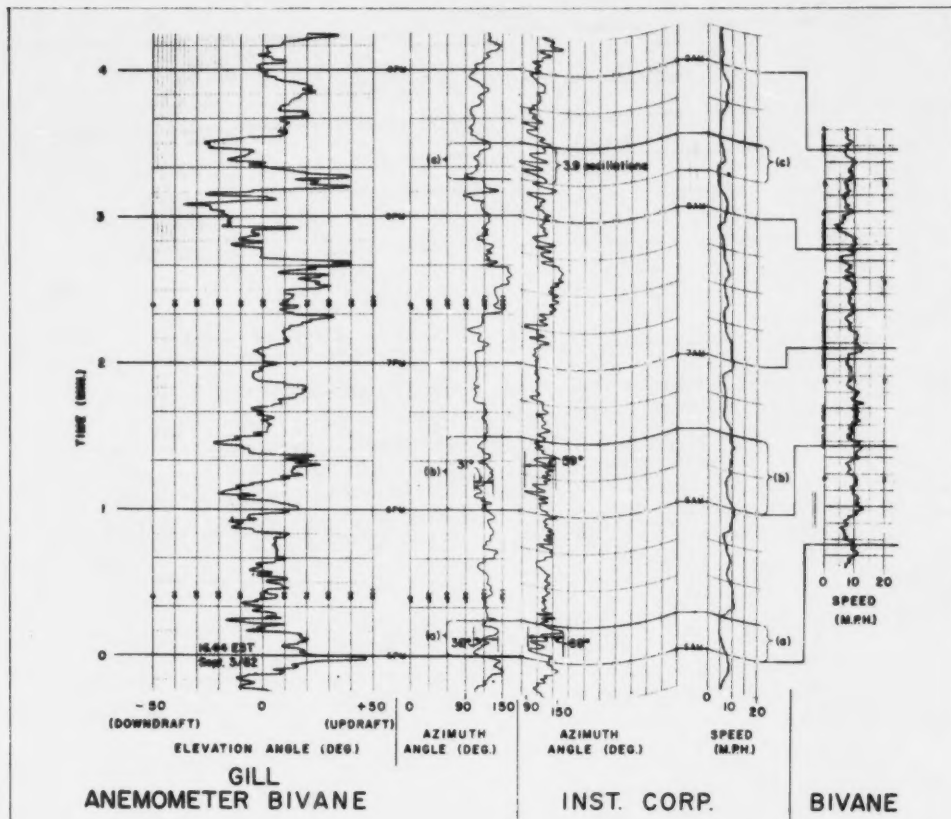


Figure 11. Simultaneous recordings of wind speed and wind direction by an Instruments Corporation, Type M Wind System and a Gill Anemometer Bivane. Instruments atop a 150-ft tower and spaced 6 ft apart.

(The approximate degree of overshoot by the Instruments Corporation vane is determined in two cases by reference to the Anemometer Bivane record—see Table 3, Note (1). The tendency of the Instruments Corporation vane to resonate with gusts near its undamped natural wave lengths is apparent from the record. The tendency is so strong that one can estimate quite closely the wind speed by simply measuring the frequency of oscillation of such a vane and multiplying by the appropriate factor. This is done in columns 5-7. Column 8 shows that such wind speed determinations can be within $\pm 10\%$ of the true speed. Such determinations are not possible when using a properly damped vane which does not resonate. It is apparent that such underdamped wind

direction sensors as the Instruments Corporation vane and the Electric Indicator vane must not be used if high fidelity wind direction recording is desired.

Examination of the two wind speed records show that the Instruments Corporation 3-cup anemometer (distance constant 21.4 ft) smooths out the speed fluctuation significantly more than does the anemometer bivane 4-bladed propeller (distance constant = 2.4 ft). Exact comparisons of speed fluctuations by the two instruments should not be made by simply reading off simultaneous speeds as the propeller measures the total speed of the wind vector whereas the 3-cup anemometer measures the horizontal component of the wind only.)

Table 3

ANALYSIS OF PORTIONS OF FIGURE 11

Section of Chart	Ind. Wind Dir. Change			Number of Oscillations of Inst. Corp. Vane During Period	Computed Speed ² (mph)	Recorded	
	Inst. Corp. (deg)	Anemo. Bivane (deg)	Approx ¹ Ampl. Ratio			Speed (mph) (Inst. Corp.)	Ratio (6) (7)
(a)	69	38	1.8	4.4	6.2 ± .6	5.7	1.08
(b)	59	31	1.9	13.5	9.7 ± 1.0	9.1	1.07
(c)				3.9	5.6 ± .6	5.5	1.02

Note (1) Since the anemometer bivane has a maximum overshoot of only 3% for gusts of any wave length and a shorter distance constant than the Instruments Corporation vane, in the analysis the anemometer bivane record has been assumed to be true and undistorted, and the overshoot by the Instruments Corporation vane determined by reference to the anemometer bivane. This section of record clearly illustrates the Instruments Corporation vane has a peak ampl. ratio of at least 1.9.

Note (2) With 4.4 gusts of probable average wave length $\lambda_d = 32 \pm 3$ ft we might expect the average speed during period (a) to be $4.4 \times 32/15$ ft/sec = $6.2 \pm .6$ mph. This compares favorably with average recorded speed (Instruments Corporation 3-cup anemometer) of 5.7 mph, within $\pm 10\%$.

As indicated above if a wind vane is exposed in a wind tunnel to a steady air flow and the vane deflected a few degrees and released we get a decaying oscillation similar to Figure 7. If the tunnel speed is doubled, the vane deflected to the same initial position and again released we get a decay curve similar to that before with the same percentage of overshoot in successive swings but of one half the time period as before. By multiplying the period of one complete oscillation by the tunnel speed we obtain the damped wave length λ_d of the vane — similar to the damped time constant t_d of the galvanometer. Each wind vane has its own characteristic damped wave length. From the decay curve of the wind vane we can obtain its damping ratio h . Equation (11) then takes the form:

$$\lambda_n = \lambda_d \sqrt{1-h^2} \quad (13)$$

where λ_n = undamped natural wave length of the wind vane. This is a theoretical distance but must be determined in order to obtain the dynamic response of a wind vane to sinusoidal wind direction fluctuations of differing wave lengths.

Several research workers*,** including the author have been, and are, doing careful work to determine the optimum damping ratio and undamped natural wave length for wind vanes that are to be used in practical air pollution studies, and, in detailed diffusion studies. The basic problem is that input signals to a wind vane are not a

*MacCready, P.B., Jr., Dynamic Response Characteristics of Meteorological Sensors, B.A.M.S., Vol. 46, No. 9, Sept. 1965, pp. 533-538.

**Wieringa, J. and F.X.C.M. von Lambert, Application Limits of Double-Fin and Coupled Wind Vanes, J.A.M., Vol. 10, No. 1, Feb., 1971, pp. 137-145.

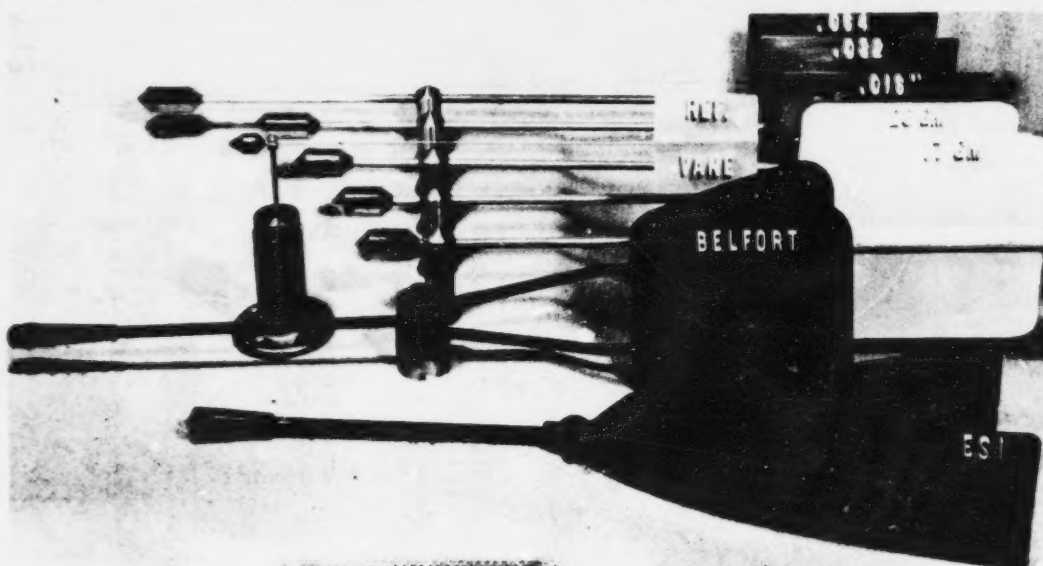


Figure 12. Set of wind vanes used in laboratory and field testing to determine the minimum damping ratio needed for good dynamic response for vanes of practical design. Four commercially available vanes (Electric Speed Indicator Company, Belfort Company, R. M. Young Company, 17 gm and 23 gm) and three experimental vanes (of one size but three thicknesses, .016 in., .032 in., .064 in. aluminum sheet) were compared with the reference vane (REF. VANE).

series of nice sinusoidal wind direction fluctuations, constant in amplitude and gust wave length, so the nice curves of Figure 10 for galvanometers do not apply to wind vanes.

Since this basic research is continuing at the present time it is desirable to outline current studies and indicate what appears to be the best design figures for vanes. It is desirable that wind vanes have good dynamic response as well as durability. Durability was overly stressed in vanes purchased by our National Weather Service and the F.A.A. in the past, at the expense of good dynamic response—the most common wind vane in the U.S.A. today (the Electric Speed Indicator Co. splayed vane, see Figure 12) has excellent durability but routinely resonates with gusts near its undamped natural wave length ($\lambda_n = 58$ ft) and shows amplitude swings of more than twice the true angular fluctuations.

In a study soon to be published the author made a rather comprehensive laboratory and field examination of the

damping ratios, undamped natural wave lengths, and field performance of some commercially available wind vanes and several experimental vanes, see Figure 12, and Table 4. For purposes of this chapter some of the results he obtained will be utilized for the first time.

From the above study using a wind vane having $h = .64$ (#1, Table IV) he determined that:

(1) Two full sine waves in succession were recorded less than 1% of the time. Thus little consideration should be given to the design of vanes for the accurate recording of two or more repeated sinusoidal wind direction fluctuations of approximately the same amplitude and frequency.

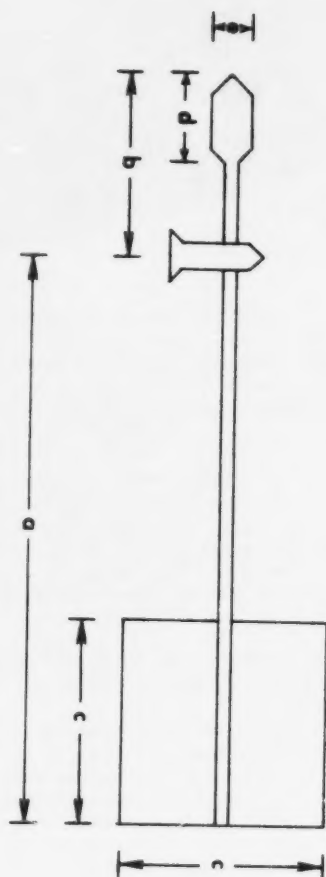
(2) One full sine wave occurred more than 3% of the time; 1/2 and 1 full sine waves occurred more than 6% of the time, so wind vanes should be designed to respond to such fluctuations with little distortion.

In view of the above an analog computer was programmed to plot out the response

Table 4

SPECIFICATIONS OF TEST VANES

No.	Vane Description	Dimensions (in.)					Tail Thickness (in.)	Weights (gm)			Damping Ratio	λ_n
		a	b	c	d	e		Tail weight	Counterweight	Shaft		
1	Ref. Vane #1	18-1/2	3-1/2	4	3/4	.50	1/16 + 1/4	3.1	13.8	1.8	.03	6.0
2	Ref. Vane #2	18	1-5/8	4	3/4	.50	1/16 + 1/4				.65	4.8
3	Ref. Vane #3	18	2	4	3/4	.50	1/16 + 1/4				.64	5.1
4	17-gm polystyrene	24	2-3/4	9	2-5/8	1-1/4	1/8 + 1/4	17.0	311.9	29.0	.49	14.1
5	23-gm polystyrene	24	4-5/8	9	2-5/8	1-1/4	1/8 + 1/4	23.0	310.0	44.6	.44	15.6
6	.008 alum.	24	4-1/4	9	2-5/8	1-1/4	.008	30.7	310.8	29.1	.43	14.5
7	.016 alum.	24	6-1/8	9	2-5/8	1-1/4	.016	58.9	311.5	39.5	.34	19.1
8	.032 alum.	24	8-1/4	9	3-1/16	1-1/4	.032	112.5	398.0	52.2	.25	26.9
9	.064 alum.	24	14	9	3-1/16	1-1/4	.064	223.4	397.4	95.3	.18	43.5
10	Belfort	16	31-1/2								.16	26.7
11	E.S.I.	15	14								.14	51.5



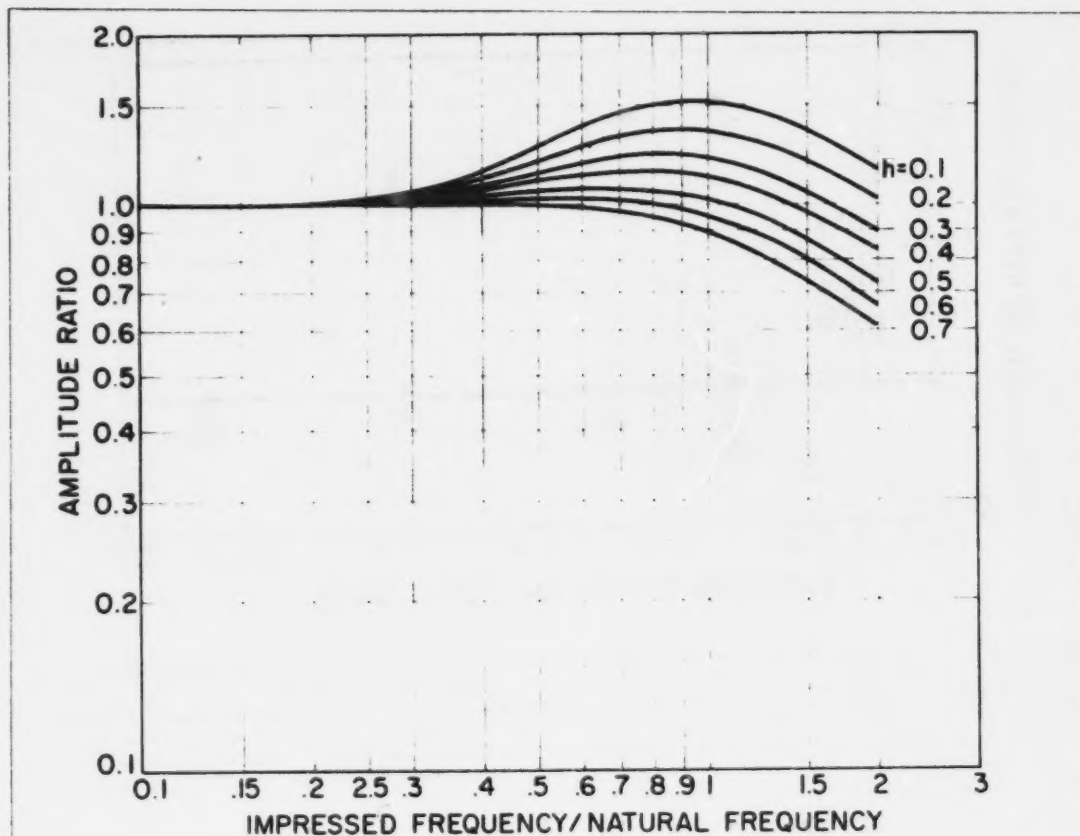


Figure 13. Relationship between the damping ratio of a wind vane and its dynamic response to a single sinusoidal fluctuation in wind direction of constant amplitude but varying frequency. (The ratio plotted is that of maximum initial deflection to the true sine wave amplitude.)

of wind vanes of various damping ratios to a single sine wave input at various input frequencies relative to the natural frequency of the wind vane. The results of this phase of the study are shown in Figure 13. From Figure 13 we can see that wind vanes having a damping ratio $h = .5$ will respond to a single sinusoidal wind direction fluctuation with little likelihood of showing more than 6% overshoot of the true wind direction fluctuation. From this evidence alone one would conclude that a damping ratio $h > .5$ is needed in wind vanes.

In another phase of this study the several wind vanes of Figure 13 were exposed simultaneously three at a time (along with a Climet 3-cup anemometer) to the natural wind

on a tower 150 ft above the ground and their output recorded on a multichannel tape recorder. The recorded data was subsequently played back through the Meteorological Laboratory Computing Facility and the standard deviation (or variance) of wind direction of each vane from its 3-min running mean was recorded. Analysis of a small portion of this data is summarized in Figure 14.

From the limited but representative data of Figure 14 we may tentatively conclude that wind vanes having damping ratio $h > .30$ will yield reliable data on the standard deviation of wind direction, σ_θ . Since σ_θ is one of the most important parameters used in most diffusion equations

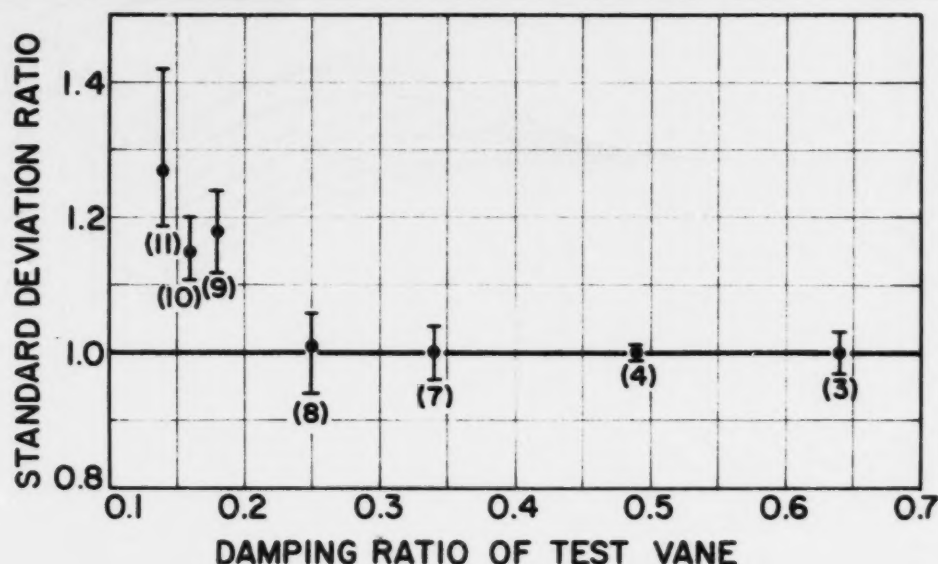


Figure 14. Relationship between the damping ratios and the standard deviation of wind direction for several of the wind vanes of Figure 13 and Table 4, compared with that of the "REF. VANE" of Figure 13, No. 2 of Table 4. (Data shown is for wind speed in range 10 to 40 ft/sec, with standard deviation of 10° to 20° in wind direction. Standard deviations of direction were made from 3-min running means of the respective vanes. Numbers in brackets refer to vane numbers in Table 4. Limits and mean for each vane determined from 20 or more data points, except for vane (4) which had only 7 points.)

it follows that accuracy in its measurement is very important. It is most gratifying to learn that one can use a relatively large and durable vane, like the flat plate aluminum vane of .016 in. thickness with $h = .34$, and yet get reliable standard deviation of wind direction with an average error of less than 1%.

MacCready and Jex* made a theoretical study of the effect of the damping ratios of wind vanes on the indicated energy spectrum of turbulence. They concluded that for this type of study wind vanes should have a damping ratio, $h = .40$ to $.45$.

From the work reported on above it is this author's conclusion that:

- (1) For detailed, theoretical studies of turbulence wind vanes having $h = 0.4$ to 0.65 , are essential.
- (2) For routine use and for most air pollution studies wind vanes having

damping ratios $h = .30$ to $.50$ are entirely satisfactory.

- (3) The undamped natural wave length λ_d of wind vanes is not nearly as important as their damping ratio. But $\lambda_d \leq 15$ ft is recommended for detailed, theoretical studies; whereas $\lambda_d \leq 30$ ft appears to be suitable for most air pollution studies.

(The latter conclusions will be surprising to many research meteorologists, as it was to the author, but from the evidence currently available the above conclusions are a logical deduction.)

Laboratory and field methods of obtaining the damping ratio and undamped natural wave length of wind vanes is given in Appendix D.

*MacCready, P.B. Jr., and Jex, H.R., Turbulent Energy Measurements by Vanes, J. Roy. Soc., 1964, pp. 198-203.

Dynamic Response of Indicating Meters and Recorders

Aronson* lists ten basic types of recorders. Of these, the galvanometer types and the null-balance types probably account for over 75% of the analogue recorders in routine use.

I. Galvanometer Types (second-order response)

For most indicators (voltmeters, ammeters, etc.) some mechanical damping is incorporated in the meter circuit to bring the damping ratio in the region of 0.4 to 0.7. If the damping ratio is not given in the specifications of such instruments, it can easily be obtained by the use of a circuit similar to Figure 6.

Most direct-writing galvanometer recorders (such as Esterline-Angus and Texas Instrument) incorporate some internal damping to permit movement of the recorder without shorting of the terminals. The manufacturer usually specifies the value of this damping factor or provides a set of typical response curves of the instrument for step function input of varying internal resistance. Fast-response recorders (such as Sanborn, Brush, etc.) are not damped in this way, but again the manufacturer supplies the dynamic response of the sensor. With all of these recorders the manufacturer's recommended circuit resistance should be used for best dynamic response.

II. Null-balance Potentiometer Recorders

Quoting from Aronson:

"Null-balance recorders are servo-operated devices that are generally

referred to as potentiometers. The basic advantages of the null-balance potentiometer are (1) high sensitivity, down to microvolt signals, and (2) independence of lead length. The sensitivity is realized by the inherent amplification in the servo system; independence of lead length is realized by cancelling out the input signal so that no signal flows at balance.

"These two basic advantages are gained at the expense of response speed; potentiometers cannot operate at speeds faster than about 1/4 sec full-scale pen travel, limiting the response to signals of less than 1 cps. However, at these frequencies the potentiometer principle opens up vast areas for recording."

Most null-balance recorders have first-order response, and therefore, show no overshoot for a stepwise input. In the specifications of such instruments it is usual to state the time for the recorder to indicate 90% or 99% deflection after application of the step function. If either of these is given, it is a simple matter to obtain the time constant of the recorder by reference to Table I.

Null-balance potentiometers are made in many different forms. Some types could have a second-order response; but these provide enough damping that negligible or no overshoot occurs with the sinusoidal input.

First-order response can be expected from most null-balance recorders.

*M.H. Aronson, "Basic Types of Recorders," Recorder Manual. 1962 and 1964 Editions, Instruments Publishing Company, Inc.

Dynamic Response of Sensors Plus Recorders

I. First-Order-Response Sensor; First-Order-Response Recorder

With this combination, where the time constants of both the sensor and the recorder are known, the dynamic response of the system may be obtained simply by use of Equation (6). Such a system will never overindicate fluctuations.

II. First-Order-Response Sensor; Second-Order-Response Recorder

If the input sensor is slow in response relative to the recorder, then the recorder damping ratio will approach 0.64 independently of circuit resistances. But if the response of the sensor is very fast relative to the recorder, the sensor will follow sinusoidal fluctuations in the variable without overshoot; to avoid overindication of the input variable the circuit resistance of the system must be designed so that the recorder damping ratio is 0.60 or greater. (Example 1: Consider a thermocouple sensor having a time constant of 20 sec and a galvanometer recorder having a natural frequency of 1.0 cps (e.g., Texas 0-1 ma recorder). From Figure 3, for the sensor to respond to 90% of the

sinusoidal fluctuations $T/P = 0.08$, $P = T/0.08 = 250$ sec, or the impressed frequency to the recorder = 1/250 cps. Referring to Figure 9, impressed frequency/natural frequency = $1/250/1 = 1/250$ which is off scale to the left. Thus the recorder would faithfully follow the fluctuations without distortion whether $h = 0.1$ or $h = 1.0$ or higher.

Example 2: Consider a hot wire anemometer, whose time constant is 0.1 sec, connected to the same recorder. From Figure 3, for the sensor to respond to 95% of speed fluctuations, $T/P = 0.05$, $P = 0.1/0.05 = 2$ sec, or, the impressed frequency = 0.5 cps. In Figure 9 when impressed frequency/natural frequency = $0.5/1.0 = 0.5$ the damping ratio should be 0.60 or greater if no overindication of wind speeds is to be recorded. If the circuit resistance were such that $h = 0.60$ for this recorder, the sensor and recorder would be almost ideally matched for good dynamic operation).

III. Other Combinations

The techniques just discussed will also apply to these combinations: second-order-response sensor with first-order-response recorder; and second-order-response sensor with second-order-response recorder.

Appendix A

Equipment and Techniques to Obtain the Time Constants
of Temperature Sensors

As indicated in Figure 1, to obtain the time constant of a temperature sensor it is desirable to transfer the sensor from an environment of one steady temperature to a new environment at a different steady temperature. The fluid in the new environment should be the same (e.g., air or water) as that in which the sensor will be used, and moving at the same rate as it will be in use.

In the laboratory one can construct a small double-duct wind tunnel as sketched below.

The duct of one blower has a resistance winding in it that is connected to a three-heat switch shown, so as to heat the air in that duct to 50°F or more above ambient temperature (when the flow rate is low). The blower motor is operated at 115 volts, with flow rate being adjusted by sliding doors at the entrance to each blower. The temperature sensor to be tested is placed in the movable duct; the duct moved to the unheated duct position; the flow rate adjusted to the desired test condition (an Alnor Velometer is excellent for this work); the

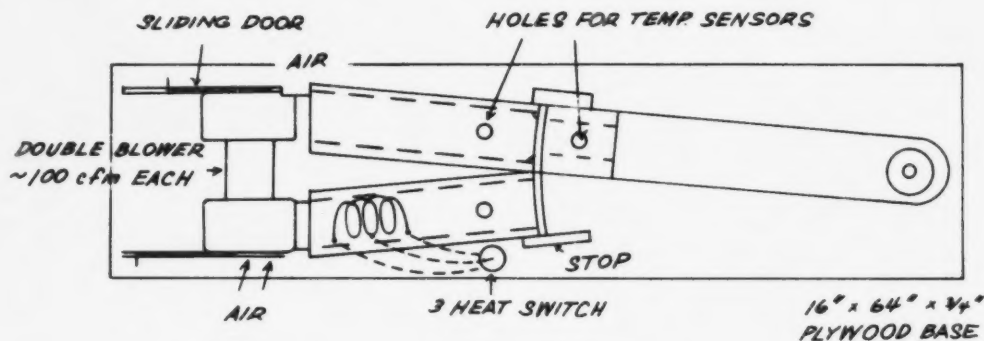
movable duct swung to the hot air duct; heat turned on; and slide on hot air intake adjusted to provide desired temperature rise. When sensor is at a steady temperature, the moving duct is rapidly swung to ambient air duct and observations started at time $t = 0$ sec. Data is plotted as in Figure 1 and the time constant obtained.

When one does not have a small double-duct tunnel, approximate temperature time constants may be obtained by relatively simple means as indicated below.

APPROXIMATE METHODS OF OBTAINING TIME CONSTANTS

(1) For an artificially ventilated sensor (such as a thermocouple or resistance thermometer mounted in a Climet or R.M. Young Co. ventilated temperature sensor):

With the sensor circuit and the ventilator in operation, suddenly transfer the inlet tube from the fairly steady temperature of a heated room to the relatively steady lower temperature of the



Dynamic Response of Sensors

wind outside. (Preferably wait for a day when the temperature difference is 30°F or more. If it is difficult to take the whole instrument outside, raise a window and rapidly transfer the inlet tube from the warm inside air through a partially opened window, into the colder outside air.) Read and record the sensor temperature readings at 10-sec intervals from 30 sec before transfer until readings become almost steady at the new outside air temperature. Plot the resultant temperature observations against time on linear graph paper as in Figure 1. From Table I it will be noted that 95% response is obtained in $3.0T$ sec. Determine the elapsed time for 95% response and divide by 3 to get the approximate time constant of sensor.

(2) For non-artificially ventilated temperature sensors (such as an ordinary mercury-in-glass thermometer, or, a thermistor probe in a stainless steel protecting tube):

Again, a stepwise temperature change is needed. Accordingly insert the sensor in a protective tube (e.g., closed cardboard tube, for thermal lag) and place the sensor and tube in an environment 30°F (or more) warmer or colder than the outside air temperature (e.g., refrigerator, or, warming oven) until they have reached a steady temperature. Then transfer the sensor in its protective tube to the thermometer shelter (or other location where it will be used); rapidly remove case and start taking thermometer readings at 10-sec intervals until readings become steady. Plot observations as in Figure 1 and obtain time constant as indicated above.

Appendix B

Equipment and Techniques to Obtain the Distance Constants of Anemometers

As indicated in the text it is desirable to subject the anemometer to a stepwise change in wind speed so as to plot the response data and obtain the time constant as shown in Figure 1. But it is difficult in both the laboratory and the field to initiate a sudden change in wind speed from one fixed value to another fixed value as a step function. Schubauer and Adams developed a very practical technique that is almost universally used now—that of holding the anemometer cups (or propeller) from turning (speed = 0 ft/sec); suddenly releasing the anemometer cup wheel (at time to = 0), and obtaining the acceleration curve, similar to Figure 1.

The wind tunnel of the Department of Meteorology and Oceanography, The University of Michigan was designed for the dynamic testing of anemometers and wind vanes. It is an inexpensive tunnel but is almost ideal for such work. It has a rectangular working section 24 in. high x 36 in. front to back; and 60 in. in length. The speed is continuously adjustable from 0 to 40 ft/sec. It is powered by a 5 hp Graham Variable Speed Drive. For light, fragile anemometers tests are conducted at say 8, 12, and 16 ft/sec. For more rugged sensors tests are usually conducted at 12, 24 and 32 ft/sec.

When a wind tunnel is not available one or other of the techniques described below might be used. These techniques will give "ball park" figures, probably accurate only to within $\pm 20\%$ of true, but still much better than one could guess.

ANEMOMETER ON TOWER TECHNIQUE

If the anemometer is mounted on a tower and operating normally, wait for a period when the wind speed is very steady in the region 10 to 20 mph, say 15 ± 2 mph (as for example, on an overcast day; or early in the morning following a clear night). If the instantaneous speed is being recorded on a strip chart recorder (analog trace), adjust

chart speed to fast speed (say 12 in./min, or even 3 in./min); have a colleague on the tower slow down and stop the cup wheel (or propeller), holding it stopped for a few seconds; suddenly release, allowing anemometer to turn freely for 20 to 30 sec; then repeat experiment 3 or 4 times. (The tower man should avoid blocking the air flow past the sensor during such runs.)

From each acceleration trace one can find the instant the anemometer reached its first maximum deflection, say 16 mph (24 ft/sec.) From Table I we see a sensor reaches 90% of a new steady state in 2.3T sec. Then measure elapsed time for anemometer to go from 0 to 14.4 mph (90% of 16 mph). Suppose this elapsed time was 2.8 sec. Then the approximate time constant would be 2.8/2.3 sec, and the approximate distance constant of the anemometer would be $(2.8/2.3 \text{ sec} \times 24 \text{ ft/sec}) = 29 \text{ ft} (\pm 20\%)$.

Similarly evaluate the other tests and average the results.

If a fast chart speed is not available, then timing to go from 0 to approximately full deflection is reached in 3.0T and 99% in 4.6T sec. So if we time the period to reach 95 to 99% full scale and divide by 4 we will get the time constant (and thence the distance constant) within about $\pm 25\%$. By obtaining 8 or 10 values of the distance constant by this technique one should obtain a value within $\pm 20\%$ of true.

AUTOMOBILE TECHNIQUE

In this technique the anemometer is made to pass through the air at an almost steady speed instead of the air blowing by a stationary anemometer. The speedometers in recently built American cars are supposed to read 9-11 mph at a true speed of 10 mph; 20-22 mph at 20 mph; and 30-32 mph at 30 mph. This is sufficiently accurate for our tests. (If one is doubtful of their speed calibration

Dynamic Response of Sensors

it can be checked for true value, $\pm 5\%$, by driving the car at a steady 10 mph (or 20 mph) and obtaining the number of seconds to travel 1.00 miles, as shown by odometer. These are usually correct within $\pm 3\%$ on all modern cars.)

The anemometer is mounted on a pipe that projects horizontally out the back windows of a sedan and locates the cups 1-2 ft out from the car on the right side. Three persons are required for the determination—a driver to maintain a constant speed of say 10 ± 1 mph; a man in the back seat to hold the pipe rigidly against the front seat, and with the anemometer in the vertical position; and the observer who can stop the cup wheel; and operate a stop watch to time the period from release until the test meter voltage shows 95 to 99% full response.

The tests should be conducted when the wind is nearly calm, preferably not over 3 mph. (If one waits till early evening after a sunny day, or early morning following a cloudless night the wind is often below 3 mph.)

The tests should be conducted as indicated above to obtain 6-10 observations for 95-99% response (4T) at say 10 mph (and 20 mph if large cup wheels are used.) The data is analyzed as indicated in the preceding section.

Appendix C

Cosine Response of a Helicoidal Propeller

The propeller anemometer, shown below (1a) is most commonly used in conjunction with a wind vane. In this configuration, the propeller anemometer will measure the horizontal wind speed. In the bivane configuration, shown in 1b, the propeller anemometer will measure the magnitude of the velocity vector. Figure 1c shows another configuration involving the propeller anemometer that will also indicate the magnitude of the velocity vector. It is this UVW configuration that makes maximum use of the inherent cosine response to off-axis wind directions as shown in the graph on the following page.

As shown in the graph, when the wind is blowing parallel to the anemometer shaft (wind angle = 0°), the propeller is exhibiting 100% response. As the wind deviates from the along-axis direction, the indicated magnitude is decreased by approximately the cosine of the wind angle as shown in the graph. This effect is inherent in the helicoidal design of the propeller. This trait makes the propeller anemometer an ideal sensor for measuring the along-axis component of the velocity vector and therefore, with the UVW anemometer, the velocity component in the three principle directions are easily obtainable.

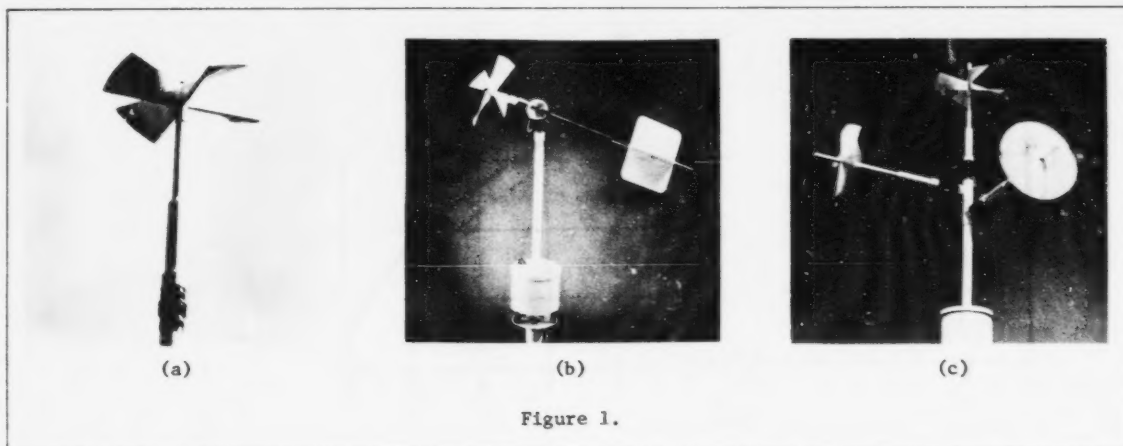
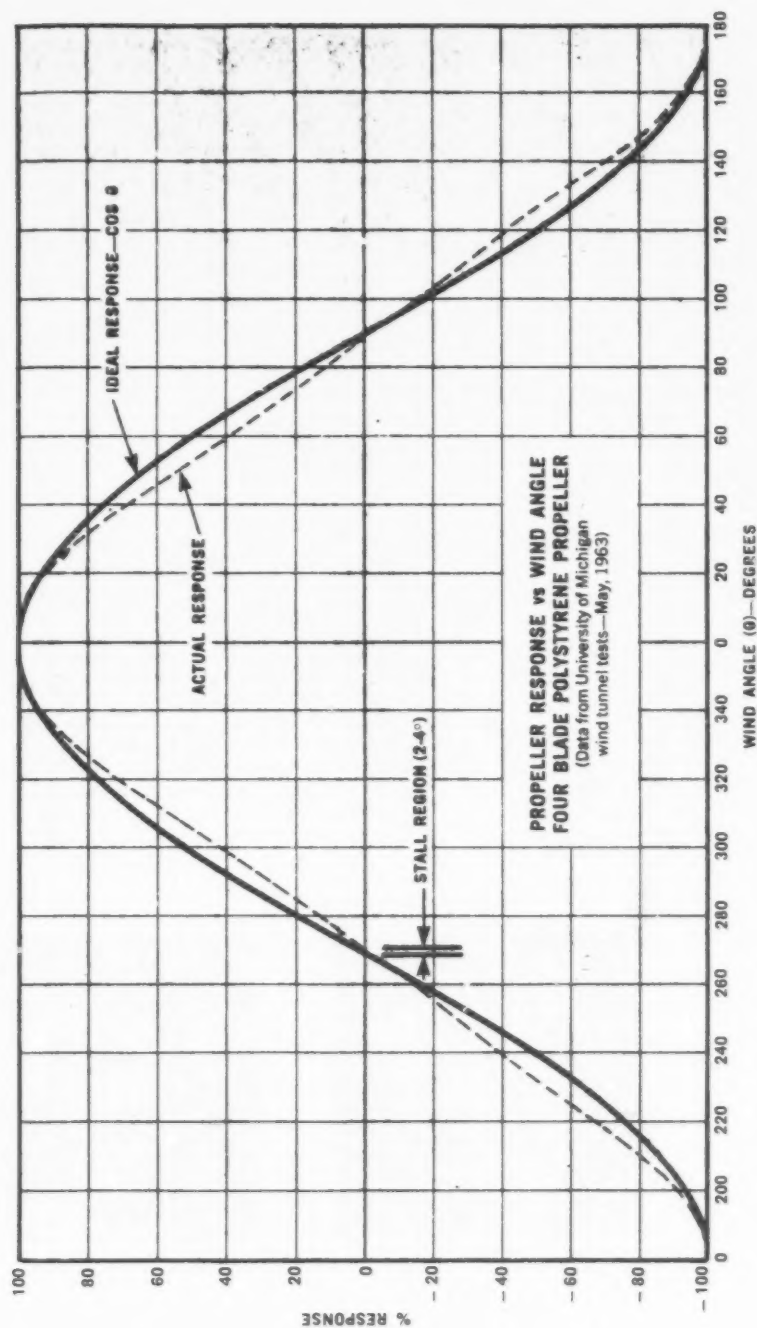


Figure 1.



Appendix D

Equipment and Techniques to Obtain the Damping Ratios
and Damped Natural Wave Lengths of Wind Vanes

As indicated in Appendix B, wind vanes are normally tested in wind tunnels. The techniques used to get the damping ratio (h), the damped natural wave length (λ_d), and the undamped natural wave length (λ_n) are given in the text, section A 2iv.

If one does not have access to a wind tunnel one can get "ball park" figures (within $\pm 20\%$) by employing the "Automobile Techniques" discussed in Appendix B, but using wind vanes instead of anemometers.

From Figure 7 it is apparent that if a vane of damping ratio $h = .16$ were deflected to the side about 30° from the wind flow, and released, it would oscillate back and forth crossing the zero line about 5 or 6 times before the deflection decreased to about $1/10$ of its initial value. Since we found the vane to oscillate about $\pm 3^\circ$ from its mean position outside a car, the writer prepared the following table:

Then, by travelling at say 10 mph with a light responsive vane (or 20 mph with a heavier vane where bearing friction is significant) under nearly calm conditions (as outlined in Appendix B above), deflect the vane about 30° from normal flow; release; and count the number of oscillations past the zero line until deflection about $\pm 3^\circ$. Repeat the experiment several times to get a reliable average value for the number of oscillations past zero. Using this average and the table above determine the approximate damping ratio (h) of the vane.

The experiment is repeated but this time the elapsed period between release and one full oscillation of the vane is measured. if the damping ratio $h \geq 0.4$. (If $h > .4$ the damped period for $1/2$ oscillation must be measured and this multiplied by two to get the damped period for that particular car speed.) Several determinations at speeds of 10 and 15 mph (15 and 22 ft/sec) should be obtained to get a value within $\pm 20\%$ of true for the damped natural wave length (λ_d) of the vane.

Damping Ratio of Vane	Number of Oscillations Past Zero After Release for Deflection to Reach 10% of Initial Deflection
0.10	10 to 11
.15	5
.20	4
.25	3
.3	2-3
.4	2
.5	1
.6	1

Appendix E

Sensor Specifications for Wind Instruments

compiled March, 1971

Daniel A. Mazzarella, Science Associates, Inc., Princeton, N. J.

Figures from Manufacturers' Data shown without brackets; from Research Reports, with brackets

Dynamic Response of Sensors

Sensors	Damping Ratio	Distance Constant 63% Recov'y ft.	Delay Distance 50% Recov'y ft.	Damped Natural Wavelength ft.	Undamped Natural Wavelength ft.	Maximum Overshoot with Sinusoidal Fluctuations %	Threshold mph	Accuracy %/mph/°	Range mph/°
S.A. #400 MRI #1071	.5-.6	8	8				<.75 <.5	±1% ±1%	>100
S.A. #408 R.M. Young #12001	.44	8.9	3.1	17.2			1.0-1.2		50/100
S.A. #4-120 Bendix #120	(.266) ^a (.29) ^b (.28) ^c	~34 ~15(15) ^c (15.3) ^e (19) ^d		(41) ^b (41.9) ^a (47) ^d	(48) ^c	(58) ^c	2.5-3 1.75-2		360/540° 100/200 100/200
3-B1'd Prop. 6-B1'd Prop.				(31.5) ^b	(58) ^c (57) ^d	(105) ^c	2-3		360°
S.A. #424 Elec. Spd. #F-420C	(.14) ^c (.17@ 3mph) ^b (.12@ 81mph) ^b	(26) ^c (26.2) ^e					2.3		100/170
S.A. #426 Wong EcoWind III	.5-.55	~5-10	~5-10	~5-10		15	.75		
S.A. #435 RAIN		~5 ~5-10(10.2) ^e					.75	.5@20-30 mph	
S.A. #441 Climet CI-26	.4						.5 .7(.8) ^g	±2% ±2%	150 125, call b 50/100
							<1 <1.25	±5° ±2% or .25mph	360/540° 100

S.A. #442(2)A Casella #T-16108/2)	Cups				.2	34
S.A. #452-1 R.M. Young #27100 #27101	4-B1'd 9" Prop. 4-B1'd 7 1/4"	3.1 2.7			.3-.5 .5-.8	50 70
S.A. #458 HRI #2040	Vane Cups	.5-.6 8			<.75 <.5	±1% ±2%
S.A. #490 Teledyne/ Geotech #15638, Dir. #15648, Spd.	Vane Quick I Quick II Standard	.6 @ 10° .4 @ 10° .17 @ 10° (.1-.2) ^h	5.7 3.7 5.0(4.7) ^h	7.5	.5 @ 10° .7 @ 10° .75 @ 10°	360/540° 360/540° 360/540°
	Speed Plastic Cup		5(3.9) ^h		.75(.5) ^h	±.15mph or 1% to 90
S.S. Cup			8		.75	±.15mph or 1% to 90
S.A. #493 Climet C1-25	Vane, Std. Spl Cups	.4(.4) ^j .6(.48) ^j (.44) ⁱ (.6) ⁱ (2) ⁱ 5	(12.8) ⁱ (10.8) ⁱ (4.0) ^j (3.5) ^j (11.4) ⁱ (7.6) ⁱ (25) ⁱ (5) ⁱ		.75 .6	±3° ±1mph 360/540° 360/540° 110, Calib to 90
SERIES 50 Teledyne/ Geotech	Vane Quick I Quick II Cups Staggered- Six	.6 @ 10° .4 @ 10° 3.3(3.2) ^h	5.7 3.7		.70 @ 10° ±2° .93 @ 10° ±2°	
	Plastic Cups	5			.5	±1% or .15mph 90
	S.S. Cups	8			.75	±1% or .15mph 90
TYPE L #5-120 Belfort Instrument Co. 3-B1'd Prop.	Vane				.75	125
					5 @ 8°	±1% 360-folded
					3	±1% output 120/240 voltage
TYPE M Belfort Instrument Co. Cups	Vane	(.20) ^c	(21) ^c	(31) ^c	5 @ 5°	±1% 150
						±1%

Dynamic Response of Sensors

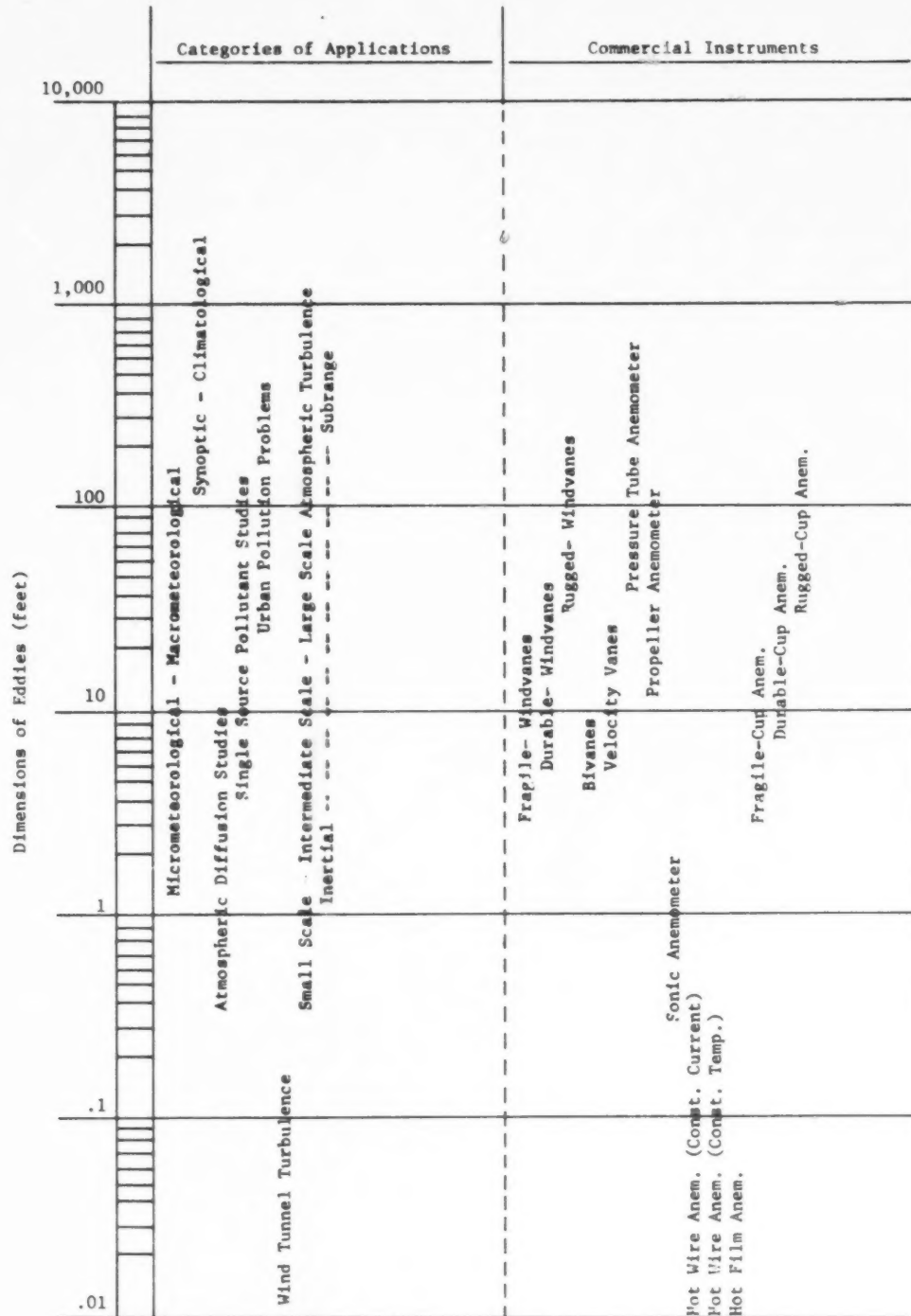
Sensors	Damping Ratio	Distance Constant 63% Recov'y ft.	Delay Distance 50% Recov'y ft.	Damped Natural Wavelength ft.	Undamped Natural Wavelength ft.	Maximum Overshoot with Sinusoidal Fluctuations %	Threshold Accuracy Range mph	Accuracy %/mph/° mph/°
SKYVANE I W101 Weather Measure		.62 @ 30mph						
Mark I Vane	.6	2.5					±3° ~1 start ~3 track	±1 @ 25 ±5 @ 25 ~200
WD-10, WS-10 Climatronics		2.5					.25 .5	±2.5° ±1% or ±.15mph
W-1034 Weather MeasureCups	.4	3.5						360/540° 125
High Freq. Tach.							.75	
3-Cup-L		5					.6	±1% or 100
6-Cup-L		3.5					.45	.15mph, 100
3-Cup-S		6					.7	greatest 100
6-Cup-S		5					.6	100
D.C. Generator								
3-Cup-L		8					.9	±1% or 100
6-Cup-L		6					.8	.15mph, 100
3-Cup-S		8.5					.95	greatest 100
6-Cup-S		7					.85	100
Model 106 Wind Profile Sensor Cups C.W. Thornthwaite Associates		2.7					.2	32
Model #143 Vertical Velocity Anemometer C.W. Thornthwaite Associates		2.9 @ 10°					.6	±1 count/±14.5 1.4' vertical air
No. 35001 Gill Prop. Vane R.M. Young Co.	.47	2.4 3.1	2.9	19.0	16		.4-.7 .3-.5	90 70

No. 21002 Anemometer Pivane R.M. Young Co.	Vane-Horiz..63(.60) ^c Vane-Vert. .63(.60) ^c 4-B1'd Prop.	3.1(2.4) ^c	3.1 3.1	19.0 19.0	14.8(14.4) ^c (14.4) ^c	2 (2) ^c 2 (2) ^c	±50 100
BIVANE Climet C1-10	Vane-Horiz..6 Vane-Vert. .6						±1° ±1° 360°/540° ±60°
AXIOMETER #018-1, C1-12 Climet Inst.	Vane-Horiz..6 Vane-Vert. .6 4-B1'd Prop.	3					±3° ±1° ±1° or ±12 or 100 360°/540° ±60° 100(125) ¹
VECTORVANE #1053 MRI	Vane-Horiz..4-.7(.6) ^k Vane-Vert. .4-.7(.6) ^k 4-B1'd Prop.	2-3(2.4) ^k 2-3(2.4) ^k	2-3(2.4) ^k 2-3(2.4) ^k	10.4 10.4		<10 <10 <1	360°/540° ±60° 100(125) ¹
#'s 6040, 6533 Teledyne/Gurley Cups	Vane						±2° 0/180° 360/180° 100
Dines Pressure Tube Anemograph Casella W1500 Model 198	Vane Pres. Tube Piezoelectric	(.55) ^m	(48.6) ^m				1.15>3.5 100/200 (<.06) ⁿ (±2% of ⁿ reading) 175
Sonic Anemometer Transducers (Standard orthogonal array measures over path length of 8" (20cm), a modulated pulse of 250,000Hz, making 400 measurements/sec) ⁿ							
Type N-7B Velocity Probe Hastings- Raydist	Omnidirectional Heated Thermopile	Response Time: .5 sec.					5/30/>100 mph
Model 1080 Total Vector Anemometer Thermo- Systems, Inc.	Electrically heated, Split-Film Platinum resistors, (Quartz-coated)	Response: DC to 1 KHz					Meg. Acc'y: Usable: ±3% of 340 mph reading & St'd: ±0.05% full 200 mph scale, 0/204mph Dir. Acc'y: ±3° for two inde- pendent dir. angles

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- k. Lockhart, T. J., "Bivanes and Direct Turbulence Sensors," Meteorology Research, Altadena, Calif., (Paper presented at NAPCA, Durham, N. C. June 19, 1970).
- l. Giblett, M. A., "The Structure of Wind over Level Country," Meteorological Office Geophysical Mem. 51, 1932. (Note: While the values shown are assigned to Casella's #W1500 instrument, it is assumed that the Dines Pressure Tube Anemograph tested by the National Physical Lab. was essentially the same in dynamic characteristics as the equipment in use today. Historically, the Dines instrument was among the earliest wind instruments to be subjected to rigorous analysis).
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Section Four

TEMPERATURE MEASUREMENT

Temperature Sensors and Transducers

Temperature Lapse Rate Measurement

Temperature Sensors and Transducers

Ronald C. Hilfiker

INTRODUCTION

Temperature is defined as the condition of a body which determines its ability to communicate heat to other bodies or to receive heat from them. For example, in a system of two bodies, that which loses heat to the other is said to be at a higher temperature. It can also be shown from statistical mechanics that temperature is proportional to the average kinetic energy of the component molecules.

The kinetic energy of the component molecules also effects other physical characteristics of the substance. Therefore, with proper calibration, the changes in these characteristics can be used to measure changes in temperature. The most common physical parameters that are used to detect the temperature of a substance are:

- 1) Thermal Expansion
- 2) Electrical Resistance
- 3) Thermo-Electricity

There are other parameters, such as vapor pressure changes in a gas, and propagation of sound, that form the basis for more exotic temperature sensors, but this discussion will be limited to the above properties.

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THERMAL EXPANSION TYPE SENSORS

At standard temperature and pressure, the volume of most substances increases with increasing temperature. There are four commonly used types of thermal expansion sensors:

- 1) Liquid in glass thermometer
- 2) Bi-metallic thermometer
- 3) Bourdon tube thermometer
- 4) Liquid in metal thermometer

A. Liquid in glass thermometer

This type of sensor is simply a capillary tube at one end of which is a bulb containing a liquid, usually mercury or alcohol. The degree of expansion of the liquid and, therefore, the length to which the capillary tube is filled is a measure of the temperature of the bulb. Assuming the bulb will achieve the temperature of its surroundings, a direct indication of the environmental temperature is obtained, providing proper scaling and calibration has occurred.

Scale - the best type of scale readings are those that are etched on the thermometer stem. Thermometers that have the scale readings printed on the backing or



Figure 1.
Scale readings
etched on glass

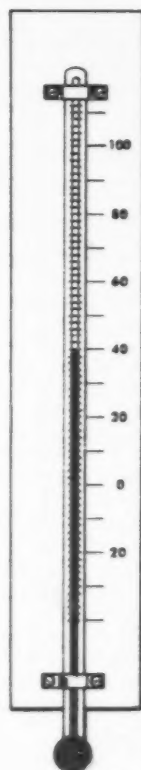


Figure 2.
Scale reading
printed on mount

mount are subject to offset errors if the thermometer assembly is jarred and the thermometer should slip in the mount. Figures 1 and 2 illustrate these two different methods of scaling.

Liquid - Mercury (Hg) is the usual liquid that is used. Hg freezes at -38.9°C , so in colder areas, an organic liquid such as ethyl alcohol is used. The freezing point of ETOH is below -100°C .

Merits of liquid in glass type thermometer:

- 1) Simple to use
- 2) Requires little maintenance
- 3) Inexpensive

The liquid in glass type thermometer has certain disadvantages that limit their use in certain applications:

- 1) Separation of the liquid in the capillary tube. This occurs if the thermometer is subject to a sudden jarring, etc.
- 2) Changes in composition of the liquid, such as distillation, which might change expansion characteristics.
- 3) Hysteresis - the expansion curve (temperature vs. length) is not the same as the contraction curve.
- 4) Parallax - an error in the reading of the thermometer. The eye must be in a plane through the end of the liquid column and perpendicular to the stem.
- 5) Does not lend itself to recording equipment.

The most common method of correcting a separated liquid column is by shaking it down, much the same as you would a medical thermometer. Grasp the thermometer by the opposite end from the bulb, and swing downward from about shoulder level, stopping abruptly. After several times, the liquid should be joined throughout the length of the capillary tube.

Only "total-immersion" thermometers are suitable for meteorological use. A total immersion thermometer is one that is calibrated totally immersed in the calibrating liquid.

Special forms of the liquid in glass thermometer:

- 1) Maximum thermometer - this type of thermometer, shown in Figure 3, will indicate the maximum temperature during the period of time since it was last reset. This period of time is usually 24 hours. In Figure 3, a constriction in the capillary tube is noticed near the bulb. The expanding liquid is forced past this constriction, but when the liquid in the bulb contracts, the column is broken at this constriction, leaving the liquid in the column to indicate the maximum temperature reached.

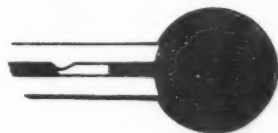


Figure 3. Maximum thermometer

- 2) Minimum thermometer - the minimum thermometer, shown in Figure 4, will indicate the minimum temperature during the time period since it was last reset. This period of time is usually 24 hours.

It can be seen from Figure 4 that there is a small rider in the liquid column. As the liquid in the bulb contracts, this rider is dragged along by the receding meniscus. When the liquid expands due to increasing temperature, the rider is left at the point of minimum temperature. The minimum temperature is read from the right hand end of the rider.

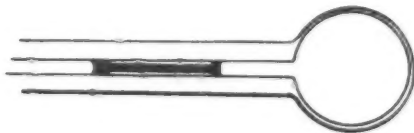


Figure 4. Minimum thermometer

B. Bi-metallic thermometer

This thermometer derives its use from the basic principle that metal expands when heated and contracts when cooled. The degree of expansion is indicated by the metals' thermal expansion coefficient (TEC).

Two metallic strips of materials having different TEC's (invar + brass or invar + steel are the most common types) are welded together. The different TEC's cause each strip of material to expand and contract differently, causing the unit to bend with a change in temperature. Figure 5 shows a bi-metallic strip element as it is used in a thermograph. With one end of the unit fixed, the other can be used, with proper linkage and calibration, to record ambient temperature.

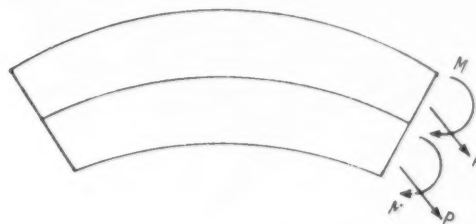
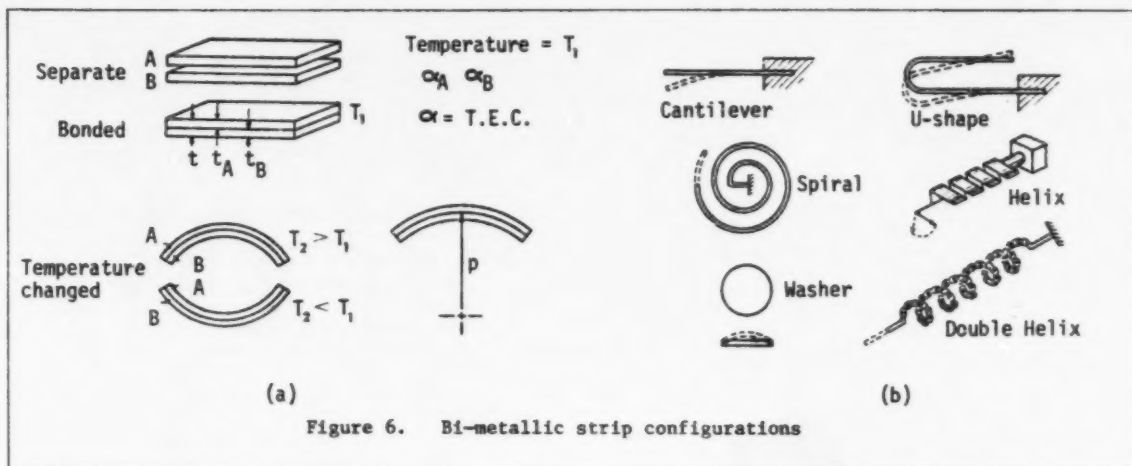


Figure 5. Bi-metallic strip temperature sensor

A wide range of configurations have been developed to meet different application requirements. Figure 6 illustrates some of these shapes and the direction of movement with change in temperature. The most common type, the strip, is shown in Figure 6a. Typical dimensions of the bi-metallic strip are 4 x 2 x .08 cm.

Advantages of the bi-metallic strip thermometer:

- 1) Very durable - insensitive to rough handling.
- 2) Adaptable to ink trace recorders by appropriate linkage attached to free end of strip.
- 3) Faster lag coefficient than the mercury thermometer. This may be an advantage or disadvantage, depending upon the application. The



time constant increases and the sensitivity decreases as the thickness of the strip increases.

The bi-metallic strip thermometer has certain disadvantages that may limit its use in certain applications:

- 1) Hysteresis effect
- 2) The zero tends to drift at first. To correct this, the strip should be subject to a number of temperature cycles that take the strip well above and below the working range.
- 3) The corrosion of the steel element in the invar + steel configuration must be prevented.

The bi-metallic strip temperature sensor has found its greatest use in the station thermograph.



Figure 7. Bourdon tube temperature sensor

C. Bourdon tube thermometer

A bourdon tube is a curved tube of elliptical cross-section that is completely filled with an organic liquid. The tube is approximately 5 cm in length. Figure 7 shows the bourdon tube sensor as it is used in a thermograph.

The operation of a bourdon tube is similar to a bi-metallic strip in that the expansion of the liquid in the tube causes the tube to bend, and with proper linkage, this bending movement can operate a pen on a thermograph.

The bourdon tube has several disadvantages that make it inferior, in many operations, to the bi-metallic strip.

- 1) Temperatures much greater or less than, the intended limits, will permanently damage the tube due to excessive internal pressure.
- 2) The tube will not withstand rough handling.
- 3) The sensor is subject to calibration change from changes in the composition of the organic liquid in the tube.

This sensor has found its most widespread use in the thermograph, but by and large, the bi-metallic strip is a more favorable sensor for this purpose.

D. Liquid in metal thermometer

In this type of sensor, the expansion of a liquid takes place in a remote bulb, and the change in pressure is transmitted to a bourdon type tube or other pressure sensor in the recorder by a small steel capillary tube. The most common type is mercury in steel thermometer. This sensor is a special form of the bourdon tube temperature sensor. Figure 8 illustrates a typical liquid in metal thermometer.

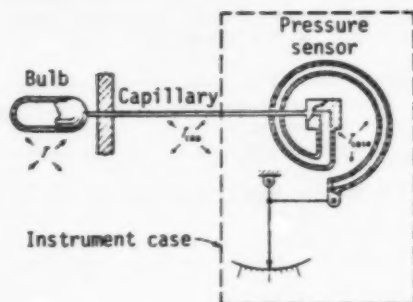


Figure 8. Liquid in metal thermometer

The volume of mercury in the capillary is insignificant unless the tubing exceeds approximately 100 ft. At lengths greater than 100 ft., the expansion of the mercury in the capillary tube due to the change in temperature of the capillary tube will cause errors in the indicated temperature. To minimize this effect, invar wire, which has a low coefficient of expansion, is inserted in the tube to occupy some of the volume. If the wire is 9/10 the capillary diameter, the mercury expansion will be compensated by the expansion of the tube.

Advantages of a liquid in metal thermometer:

- 1) Very durable instrument
- 2) Remote sensing is possible
- 3) Good sensitivity is possible

Disadvantages of this sensor:

- 1) The pressure sensor in the recorder must be temperature compensated.

- 2) Use limited to temperatures greater than -38°F (Freezing point of mercury).
- 3) The remote sensing is limited to about 150 ft.

These units have found their greatest use in such devices as "indoor-outdoor" thermometers, thermostat controls in boilers, and other industrial applications.

ELECTRICAL RESISTANCE TYPE SENSORS

Another physical characteristic of a material that can be used to detect temperature is electrical resistance. There are two basic types of electrical resistance sensors:

- 1) Resistance wire type
- 2) Thermistor type

A. Resistance wire thermometer

It has been found that the resistance of such metals as platinum, nickel, copper, silver, or iron increases with an increase in temperature by the following relationship:

$$R = R_0 [1 + a (T - T_0)^2]$$

where:

R_0 = Resistance at temperature T_0

R = Resistance at temperature T

a and b = coefficients

This property can be used to indicate the temperature of the element and, therefore, the medium it is immersed in.

Platinum is the most common metal used in resistance wires. Why?:

- 1) It maintains its calibration over a long period of time.
- 2) Platinum wire units are stable and interchangeable.

The standard resistance for R_0 is 100 Ω . The output resistance R is commonly measured by a wheatstone bridge. A typical wheatstone bridge is shown in Figure 9.

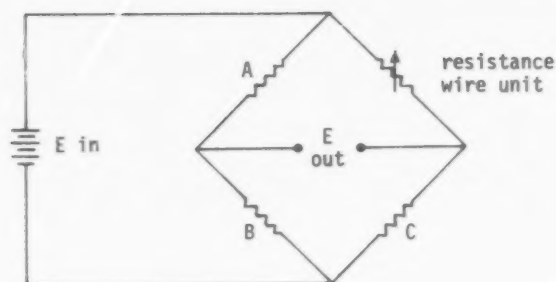


Figure 9. Wheatstone bridge

An analysis of this circuit will not be made except to say that E_{out} can either be in a deflection mode or null mode. If the null method is used, resistance A in Figure 9 is varied until E_{out} is zero. This is by far the most desirable of the two modes, since it makes the result independent of battery voltage (E_{in}) and the sensitivity of the indicating galvanometer.

There are some cautions that should be observed when using wheatstone bridges:

- 1) The resistance of the lead wires may change with changing temperatures of the lead wires. These resistances, indicated by L_1 and L_2 in Figure 10, would give a false indication of

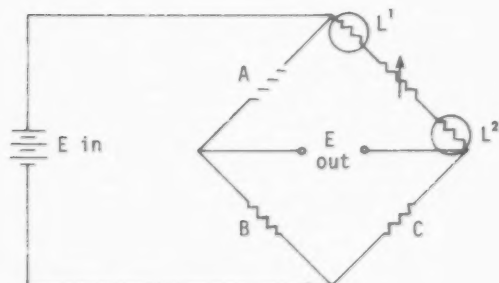


Figure 10. Wheatstone bridge showing lead wire resistances L_1 and L_2

sensor resistance change and produce errors in the measured temperature. This malady can be corrected by the 3 wire configuration of Figure 11. In this configuration, the lead wire resistances end up on different bridge legs and their resistances have a cancelling effect on the final output voltage (E_{out}).

- 2) The current passing through the lead wires must be kept to a minimum so that self heating, which changes the impedance of the resistance wire, is kept to a minimum.

Resistance wire temperature sensors have found wide-spread use where electrical and remote recording of temperature and temperature lapse rate is necessary.

B. Thermister type thermometers

A thermister is a mixture of metallic oxides (manganese, nickel, and cobalt)

$$R = R_0 \text{ EXP } \left[B \left(\frac{1}{T} - \frac{1}{T_0} \right) \right]$$

that are compressed together and heat-treated. They may take on any number of shapes, a few of which are shown in Figure 12. The resistance of this compressed mixture changes exponentially with a change in temperature by the following relationship:

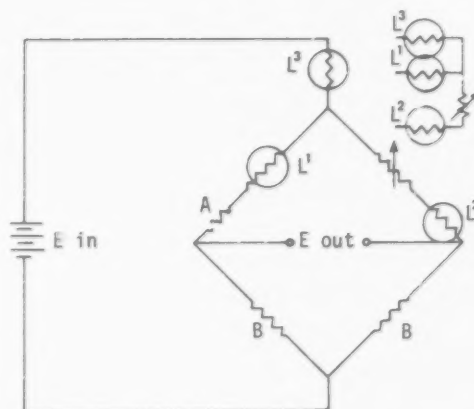


Figure 11. 3 wire wheatstone bridge

where:

- R_0 = Resistance at temperature T_0
- R = Resistance at temperature T
- B = Constant that is characteristic of the material

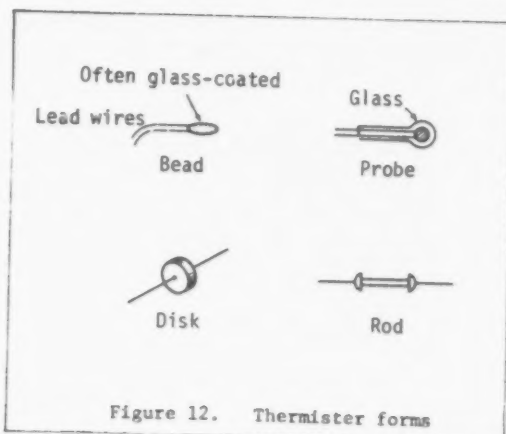


Figure 12. Thermister forms

As can be seen from the equation, a thermister exhibits a decrease in R with an increase in T . The R versus T curve is highly exponential and the sensitivity is about 2 orders of magnitude higher than that of metallic resistance thermometers.

Advantages of thermistors:

- 1) High sensitivity

- 2) Possibility of fast response (m sec - min)
- 3) Wide range of shapes are available

The only potential problems involved in working with thermistors is the fact that the R versus T relationship is extremely non-linear and the reliability of the thermister is not as great as resistance wire thermometers.

Thermistors have found their widest use in specialized studies where calibrations are frequently checked. Attempts to use them for long-term climatological type studies have led to problems.

THERMOELECTRIC TYPE THERMOMETERS

It has been found that when two dissimilar metals are brought together, as in Figure 13, and junction A is at a different temperature than junction B, a current will flow in the circuit. A voltage will be developed across the junctions that is related to the difference in temperature between the junctions by the following equation:

$$\Delta E = C_1 (T_A - T_B) + C_2 (T_A - T_B)^2$$

where:

T_A = temperature at junction A

T_B = temperature at junction B

C_1, C_2 = constants

ΔE = voltage produced across junctions A and B

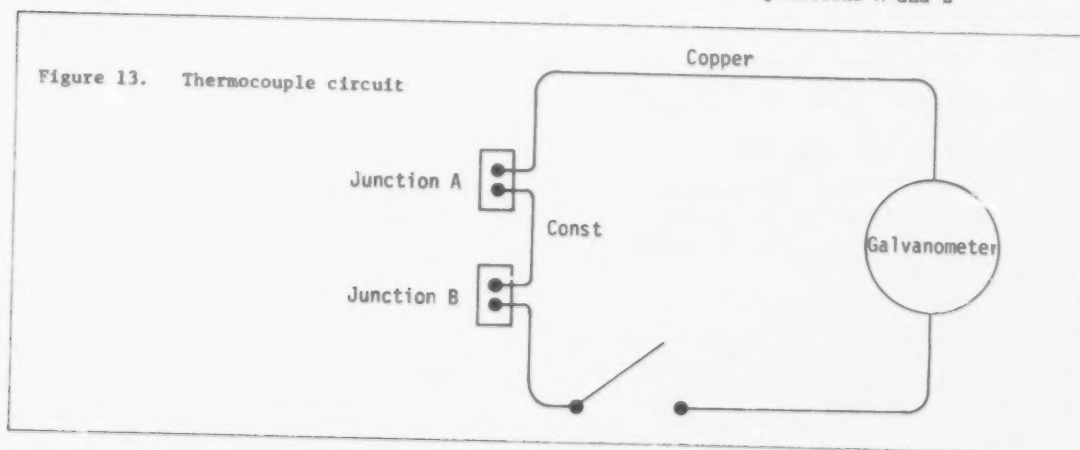


Figure 13. Thermocouple circuit

Since the term $C_2 (T_A - T_B)^2$ is quite small, the ΔE vs. ΔT curve is approximately linear. The most common metals to use in thermocouples are copper (Cu) and constantan. Constantan is a mixture of about 60% Cu and 40% nickel (Ni) with a trace of Manganese (Mn), iron (Fe), and carbon (C). As will be seen later, Cu is the most desirable metal to use for lead-in wire.

The EMF developed depends on the metals being used. At room temperature, Cu-const is 40 mv/°C. A complete list of EMF's for different metal combinations can be found in the CRC Handbook of Chemistry and Physics.

A major drawback to thermocouples arises out of their sensitivity. The voltage generated per degree change in temperature is so small a "thermopile" is needed to generate a signal of any magnitude. A "thermopile" is defined as two or more thermocouples connected in series.

Advantages of thermo-electric temperature sensor:

- 1) A wide range of time constants are available. The lag coefficient is determined by the size of the wire used and the type of junction. Time constants are available from the μ /sec range on up to sec., min., or hours.

- 2) Sensors are very durable.

- 3) No power supply is needed. The sensor generates its own voltage.

Disadvantages of thermo-electric temperature sensors:

- 1) Thermocouple systems sometimes have a noise problem from the pick-up of induction currents from nearby sources.
- 2) Whenever there is a connecting junction of two dissimilar metals, there is the possibility of contact potentials being developed. This effect can be eliminated by using copper lead wires, minimizing the junctions and keeping the junctions at the same temperature.
- 3) 20 to 30 junctions and an amplifier are needed to produce a good signal because of the low output of a single thermocouple.

Thermocouple temperature sensors have found their widest use in the measurement of temperature lapse rate in the atmosphere. This type of measurement is made extremely easy due to the inherent trait in the thermocouple of generating a voltage proportional to a temperature difference between two points.

REFERENCES:

Temperature Sensors and Transducers

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- 2) Slade, D. H., Editor, "Meteorology and Atomic Energy, 1968", U. S. AEC, Division of Technical Information, pp 277 - 283.
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Temperature Lapse Rate Measurement

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INTRODUCTION

The concentration of pollutants in the atmosphere, for a given pollutant source distribution, is dependent, for the most part, on two primary meteorological parameters:

- 1) Wind speed, direction and turbulence
- 2) Temperature lapse rate

The wind determines the initial dilution, direction of transport, and diffusion of the pollutants. The vertical variation of temperature is a prime index of the vertical turbulence, the maximum mixing depth of the pollutants and the rate at which the contaminants diffuse in the vertical.

Wind measurements have been described in previous sections, and this section will be devoted to methods of measuring the vertical temperature lapse rate.

INSTRUMENTED TOWERS

One of the most common methods for measuring temperature lapse rate is to instrument a tower with temperature sensors. Typical sensors are thermocouples or thermistors. The characteristics of these sensors are detailed in the previous portion of this section. The exposure of temperature sensors on a tower is detailed in Section Six.

Instrumented towers have some disadvantages that limit their use in air pollution studies:

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1) Most towers that are within the economic means of an air pollution agency are under 100 feet in height. Although the boundary layer lapse rate is readily obtainable with such a tower, the lack of information above 100 feet can be detrimental to certain types of studies. With a 100 ft. tower, the tops of radiation inversions, bases and tops of elevated inversions, urban heat islands and many other lapse rate related phenomena cannot be detected.

2) There are towers that reach heights of 1500 ft. and more. These towers are usually owned by radio or television stations, but are sometimes made available for meteorological instrumentation. The disadvantage of such a tower can be readily attested to by anyone who has had to service the sensors and recorders on a periodic basis. Because of the distance involved, the recorders are most economically placed at the sensor location. Servicing such recorders can be very time consuming as well as dangerous. In addition, at 1500 ft., the tops of some radiation inversions as well as most elevated inversions are still undetectable. It also should be noted that towers of this height are few and far between.

BALLOON SOUNDINGS

To measure the temperature lapse rate above 1500 ft., it is necessary to mount the sensor on some sort of airborne vehicle. One

Temperature Lapse Rate Measurement

of the most common vehicles used is a balloon. The National Weather Service has a network of balloon sounding stations. This network is described in Section Two under "Measurement of Winds Aloft." As indicated in that section, temperature sensors are used on balloons in the Rawinsonde program. Usually a resistance type temperature sensor is mounted in the Radiosonde carried aloft by the balloon, and values of temperature at different heights are transmitted back to a ground receiver. The complexity of the Radiosonde plus the fact that only about 50% of the packages are recovered, combine to make the cost of the system, \$20-\$25 per sounding, prohibitive to most air pollution control agencies. Another disadvantage of the Radiosonde method is the fact that a continuous temperature trace is not available. A baroswitch is used to cycle through the temperature, humidity and reference points producing an intermittent temperature trace which has to be extrapolated to produce continuity.

Other balloon-borne temperature lapse rate systems have been developed which are less costly to operate. Colepan Environmental Systems, Inc., has recently developed a thermistor sensor balloon system which can be used at a fraction of the Radiosonde cost.

Inherent with all balloon systems is the low recovery record as well as drift of the balloon after release. Drift produces a lapse rate which is not representative of one spot, but an integration over the balloon trajectory.

AIRCRAFT SOUNDINGS

In many instances, instrumented aircraft have been used to obtain measurements of temperature lapse rate. Nearly all types of temperature measurement systems can be used on an aircraft. Section Four describes the exposure of the sensor on different types of aircraft. Problems encountered usually stem from the vibration and shock that the recording equipment is exposed to within the aircraft but this can be eliminated with proper padding and installation. The aircraft must also be flown at a known, constant speed to allow correction for wind cooling of the sensor. These problems are easily overcome, but the fact remains that most agencies do not have access to an aircraft. Those agencies that have found success in this method have an arrangement with a local police department or radio station

to use their aircraft as a sensor platform when the aircraft is in use in traffic watches. Fortunately, morning traffic watches are at approximately the time when a morning temperature sounding would be desirable for purposes of forecasting maximum mixing depths. However, for the great majority of agencies, the cost of an aircraft sounding program cannot be economically justified.

ROCKETSONDE

Until recently, the above mentioned methods were the only practical means of measuring temperature lapse rates. The costs involved have limited their use mainly to Federal Agencies and some of the larger State Agencies.

Recently, a low cost, low altitude rocketsonde has been developed by Colspan Environmental Systems, Inc., which appears to provide a simple and economical means of measuring temperature lapse rate in the lower 4,000 ft. of the atmosphere. The system, shown at launch in Figure 1, consists of a single stage rocket, a bead thermistor carried on the nose of the rocket body, a launcher receiver, and a Rustrak recorder. The rocket is fired to a known altitude, determined by the size of the propulsion unit, where the rocket separates from the propulsion unit and descends on a parachute. The bead thermistor senses the temperature and electronics within the rocket transmit the temperature values to a ground receiver and recorder. The result is a continuous record of temperature vs. altitude. The rocket needs no Federal Aviation Administration clearance to fire, and with adequate space (about 100 yards square) complete recovery of the system is most probable. The cost of the system is about \$3,000 and each sounding costs \$3.50.

An added bonus is possible because of the known descent rates of the rocket and motor which descend under separate parachutes. With known descent rates the distance between the rocket and motor after they have returned to the ground is proportional to the average wind speed throughout the sounding layer. The orientation of the rocket with respect to the motor determines the average wind direction in the sounding layer.

The mention of any commercial product is not intended to imply endorsement by any agency of the U. S. Government.

Section Five

**SECONDARY
METEOROLOGICAL PARAMETERS
AND THEIR MEASUREMENT**

An Outline of Secondary Meteorological Parameters
and Their Measurement

Secondary Meteorological Parameters and Their Measurement

An Outline of Secondary Meteorological Parameters and Their Measurement

Daniel A. Mazzarella

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Science Associates, Inc.

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Secondary Meteorological Parameters and Their Measurement

Ronald C. Hilfiker

INTRODUCTION

In air pollution applications, certain meteorological parameters are of more importance than others. It is generally accepted that wind and temperature lapse rate are of primary importance while temperature, precipitation, humidity, solar radiation, pressure and visibility are of secondary importance. This grouping of primary and secondary parameters will vary somewhat depending on the particular study and/or site. For instance, in Los Angeles, solar radiation would most probably be added to the list of primary meteorological parameters. A study of pollutant washout or rainout would certainly consider precipitation a primary factor.

The reader is referred to Section One of this manual for the detailed discussion in "The Effects of Meteorological Parameters of Air Pollution." The measurement of wind, temperature and temperature lapse rate have been described earlier in this manual. This section will be devoted to discussing the methods of measurement of precipitation, humidity and solar radiation.

PRECIPITATION

Rainout and washout are two of the most important natural removal processes at work in the atmosphere. Larger particles and water soluble gases may be removed from the atmosphere by falling precipitation. Chemical or radioactive analysis of rain water may then follow.

Systems for measuring precipitation are generally of either the non-recording or recording type.

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1. Non-Recording Type (Standard Rain Gauge)

The standard rain gauge consists of a metal funnel 8 inches in diameter, a measuring tube having 1/10 the cross-sectional area of the funnel, and a large container of 8 inches diameter (Figure 1). Normally precipitation is funneled into the measuring tube. The depth of water in the tube is measured using a dip stick having a special scale (because of the reduction in area). Measurements with this instrument, since they are made manually, give only accumulation since the last measurement.



Figure 1. Standard rain gauge

The rain gauge shown in Figure 1 is the standard gauge that has been adopted by the National Weather Service. The standard gauge can be converted to a snow gauge by removing the funnel and measuring tube. The snow will then fall into the 8 inch cylinder and can be measured directly. Inexpensive rain gauges of the non-recording type are shown in Figure 2. Figure 2a is a miniature of the standard gauge shown in Figure 1. The "Clear-Vu" gauge shown in Figure 2a utilizes a graduated cylinder instead of a calibrated dip stick.

The "Remote-Vu" gauge shown in Figure 2b can be used where suitable ground level exposure cannot be obtained. The funnel can be located atop a pole or tower with tubing carrying the water to a suitably located graduated cylinder for measurement. This would have application in a thickly forested area.

While most gauges have a linear scale with a sensitivity of .01 inch of rain, the "weave" gauge shown in Figure 2c has a non-linear scale which allows very small rainfall amounts to be measured. This is accomplished with an expanded scale at the bottom of the gauge. This type of gauge is used extensively by farmers.

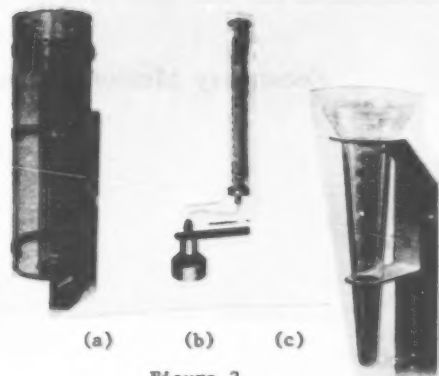


Figure 2.

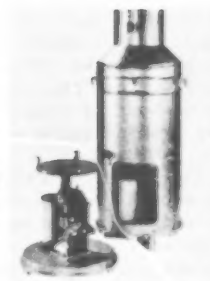
2. Recording Type

This type of rain gauge enables a detailed time resolution of occurrences and amount of precipitation to be obtained. The two most common types of recording rain gauges are the weighing bucket and the tipping bucket gauge.

a. Weighing Bucket Gauge

The type of gauge shown in Figure 3 has a funnel which channels the precipitation into a bucket which sits on a scale. The scale weighs the precipitation and moves a pen or a clock driven drum. Thus, total accumulation as a function of time is recorded on the chart. The chart is usually calibrated in inches of rainfall.

Figure 3.
Weighing bucket gauge



b. Tipping Bucket Gauge

This precipitation gauge has a bucket with two compartments beneath

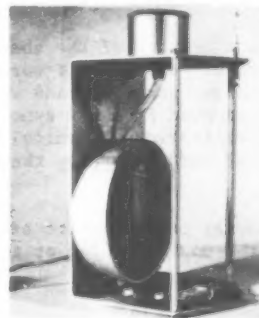


Figure 4.
Tipping bucket

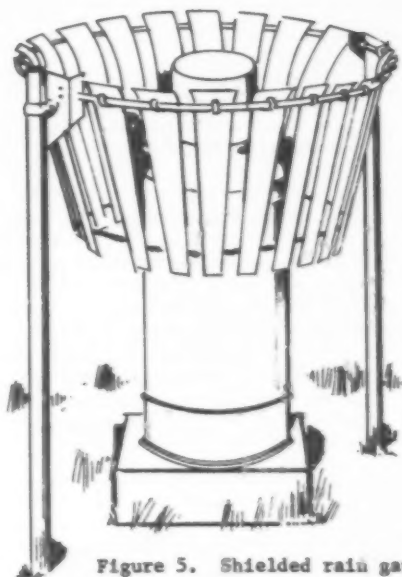


Figure 5. Shielded rain gauge

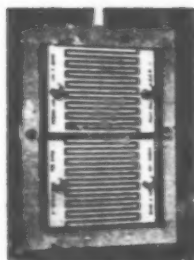


Figure 6. Rain detector for automatic precipitation collector

the collecting funnel (Figure 4). When one side of the bucket collects a given amount (usually 0.01 inch) of precipitation, the bucket tips and empties the precipitation, collecting the next portion in the other side. The bucket movements are recorded on a chart. The number of bucket movements and the time they occur indicate the rainfall amount and rate. This type instrument is not suitable for measuring snow.

Precipitation gauges such as the ones described above are known to be inaccurate under certain types of wind conditions. The major cause of inaccuracy in precipitation gauges is the aerodynamic flow in the vicinity of the mouth of the funnel. Eddy patterns are sometimes created that will divert a significant portion of the precipitation away from the intake of the gauge. In strong winds, indicated precipitation may be 10% to 30% less than the true rainfall. Methods have been devised to eliminate these errors, but none have proven completely effective. One solution to the problem involves making the intake of the gauge flush with the ground surface in uniform terrain. Another solution, shown in Figure 5, involves a windshield which can be installed as shown to reduce the distortion of the air flow around the gauge.

To record snowfall in the recording type gauges, special heaters can be installed which will melt the snow as it contacts the funnel, and keep it in the liquid state for measurement. The measurement then has to be converted to snowfall depth by various equations relating the liquid equivalent of snow at various temperatures.

For research purposes, it is desirable to analyze rainfall as to its chemical and radioactive constituents. Since it is desirable to include only precipitation samples, and not material that may fall into the collector during dry periods, a collector which opens only during periods of precipitation has been developed. The sensor (Figure 6) has two sets of adjacent wires. A raindrop falling between the wires completes an electrical circuit which removes the cover from a polyethylene container. A small heat source dries the sensor so that the circuit will be broken when precipitation ceases and also so that dew will not form and open the collector.

This instrument is illustrated in Figure 6.

Approximate costs of the gauges described above are given for comparative purposes only:

Figure 1 - Standard Gauge	\$ 70.00
2a - Clear-Vu	18.00
2b - Remote-Vu	36.00
2c - Wedge	4.00
3 - Weighing Bucket	350.00
4 - Tipping Bucket	300.00
6 - Automatic Collector	450.00

As will be the case for all of the secondary sensors, it should be noted that there is about a factor of ten difference in cost between the recording and non-recording gauges.

HUMIDITY

As indicated in Section One of this manual, humidity has a strong influence upon certain chemical reactions in the atmosphere, as well as visibility. For these reasons, it may be desirable to measure humidity in connection with an air pollution investigation. Also, some air pollutants affect receptors differently with different humidities, so measurement may be of importance in this respect.

As with precipitation sensors, humidity sensors are also of two general types, the recording and non-recording type.

1. Non-Recording Type

The bulk of non-recording humidity instruments use the wet and dry bulb psychrometer as a sensor. The principle behind a psychrometer is the reduction in temperature of a wetted surface due to evaporative cooling. This principle can be used to determine the amount of moisture in the air. The method involves obtaining a dry bulb temperature and a wet bulb temperature from a matched set of thermometers. One thermometer bulb (wet bulb) is covered with a muslin wick moistened with distilled water. The thermometer bulbs are placed in a 3 to 5 m/sec, which causes the evaporative cooling of the wet bulb. Two standard methods are used to create an airstream:

- A motor-driven fan may be used to draw air at a steady rate past the moistened wick while a reading is taken.
- A sling psychrometer has both thermometers mounted in a frame which is whirled through the air to cause the evaporative cooling.

Conversion of the wet and dry bulb temperature readings to relative humidity or dew point is easily accomplished by using psychrometric tables or humidity slide rules. The Bendix Psychron is illustrated in Figure 7.

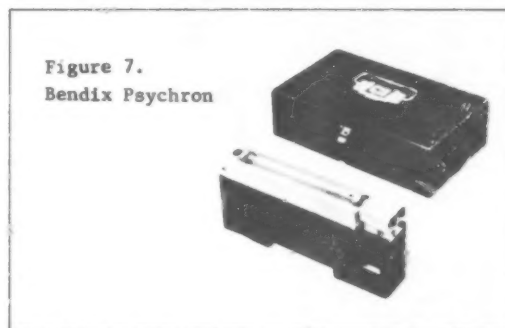


Figure 7.
Bendix Psychron

2. Recording Type

Recording psychrometers have been developed which substitute resistance wires, thermocouples or thermistors for the glass thermometers. The principle of operation is identical to the psychrometer described previously. These sensors lend themselves to remote and continuous recording through the use of self-balancing potentiometers or wheatstone bridges. These sensors and transducers are described in Section Four. One of the most common sensors used to determine relative humidity is the FAIR HYGROMETER. For about the last 150 years the hair hygrometer has been widely used in both meteorological and industrial applications. The principle of operation is simple. When human or animal hairs have been cleaned and the oil removed by treatment in ethyl ether, their length changes by about 2.5% as the relative humidity changes from 0 to 100%.

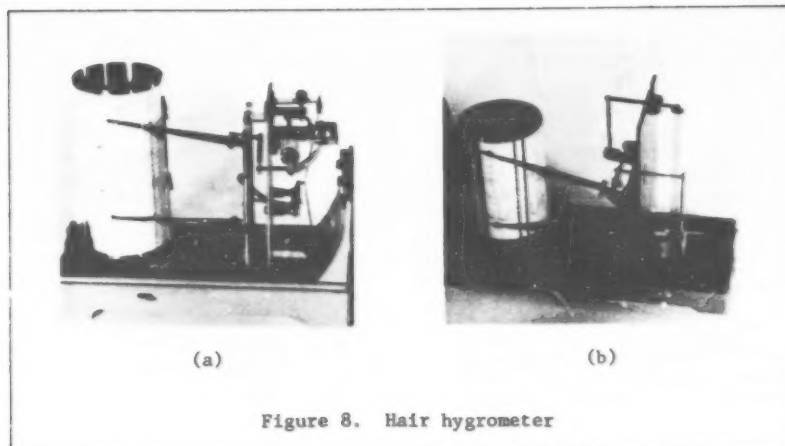


Figure 8a illustrates how this elongation principle may be used to move mechanical linkage which magnifies the movement of the hairs. This linkage is connected to a pen, as shown in Figure 8b, which indicates changes of relative humidity as a function of time on a clock-driven drum.

The relation between elongation and relative humidity is logarithmic in the relative humidity range of 20 to 100%. The elongation can be modeled by the equation $L=a+b (\log RH)$ where

RH = Relative Humidity

L = Length of the hair

a and b = constants

This relationship requires logarithmic compensating linkage in order that the scale on the chart be linear.

Hair hygrometers have several maladies which cause shortcomings in some applications. At temperatures below freezing there is a significant loss in the response time of the hairs. Also, cleaning and calibration checks must be performed on a weekly basis. Cleaning a hair hygrometer involves "painting" the hairs with distilled water. The painting is best accomplished with a camel's hair brush.

A sensor that lends itself to remove indication of humidity is the HYGROSCOPIC HYGROMETER. Salts such as calcium chloride or lithium chloride are hygroscopic and therefore absorb water vapor when placed in a moist atmosphere. Lithium chloride also changes its electrical resistance with relative humidity giving rise to what is called an electrolytic hydrometer. This principle is used directly in the radiosonde system. The lithium chloride is coated on a plastic slide which is used as a variable resistor in an electronic circuit.

APPROXIMATE costs of the humidity instruments described above are given for comparing purposes only.

Wet/Dry Bulb
Psychrometers \$15.00

Figure 7 Psychron (Battery
Powered Fan) 70.00

Figure 8 Hair Hygrometer 200.00

SOLAR RADIATION

The influence of the sun's radiation upon the turbulence of the atmosphere and upon certain photochemical reactions is sufficient to make measurements of radiation of importance. In addition, radiation may be reduced due to particulate pollution in the atmosphere. Particularly for research pur-

poses, it may be desirable to measure this effect by comparisons between urban and non-urban stations similarly instrumented.

TOTAL RADIATION

The direct radiation from the sun plus the diffuse radiation from the sky may be measured by pyranometers. These instruments are mounted so that the sensor is horizontal and can receive the radiation throughout the hemisphere defined by the horizon. The instrument illustrated in Figure 9 is of this type.

The principle of measuring the total radiation using the pyranometers shown above is based on the temperature difference between the black sectors (coated with lamp-black) and the white sectors (coated with magnesium oxide). This temperature difference, when calibrated, is a measure of the intensity of the total solar radiation. The temperatures are measured with multi-fraction thermopiles. The thermopile output can be coupled to a millivolt recorder for remote indication of total radiation.

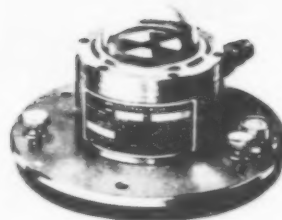


Figure 9.
Eppley "black & white" pyranometer

Section Six

**EXPOSURE OF
METEOROLOGICAL INSTRUMENTS**

Exposure of Surface Instruments

Exposure of Instruments on Towers or Stacks

Exposure of Airborne Instruments

Exposure of Instruments

Ronald C. Hilfiker

Exposure of Surface Instruments

INTRODUCTION

Exposure of instrumentation is undoubtedly one of the most important steps in any air pollution study. It is absolutely necessary to locate the instrumentation in such a manner that the measurements are representative of the area in which one is interested. In some cases, such as street level measurements in a city, it is desirable to obtain measurements of extremely local phenomena, but generally in air pollution meteorology, measurements that are representative of a fairly large area are desired. In this latter case, extreme care must be taken to ensure that the parameter being measured is not influenced by nearby obstacles.

An example of the effect of a building on regional wind flow is shown in Figure 1.

Figure 1a shows two identical aerovanes mounted on a tower approximately 20 feet south of a 12 foot high building. The only difference in exposure between the two aerovanes is the 6 foot difference in height. It can be seen from Figure 1b that when the wind is blowing from the west, both sensors are apparently free of building influence, with both wind traces indicating typical mechanical type turbulence. However, when the wind shifts to the north-west, the turbulence characteristics change markedly in the wind flow being sensed by the Bendix aerovane at the 6 foot level. At the 12 foot level, the Belfort aerovane continues to indicate typical mechanical type turbulence. Which trace is indicative of the regional wind flow? It is the purpose of this chapter to explore the concepts needed to answer this question.

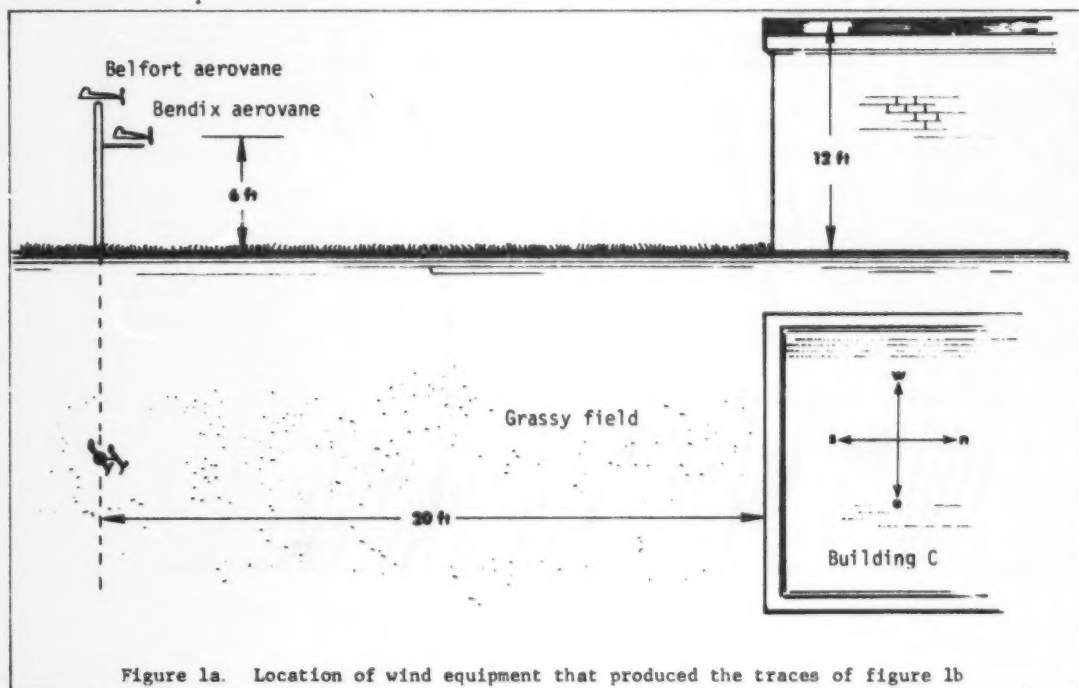
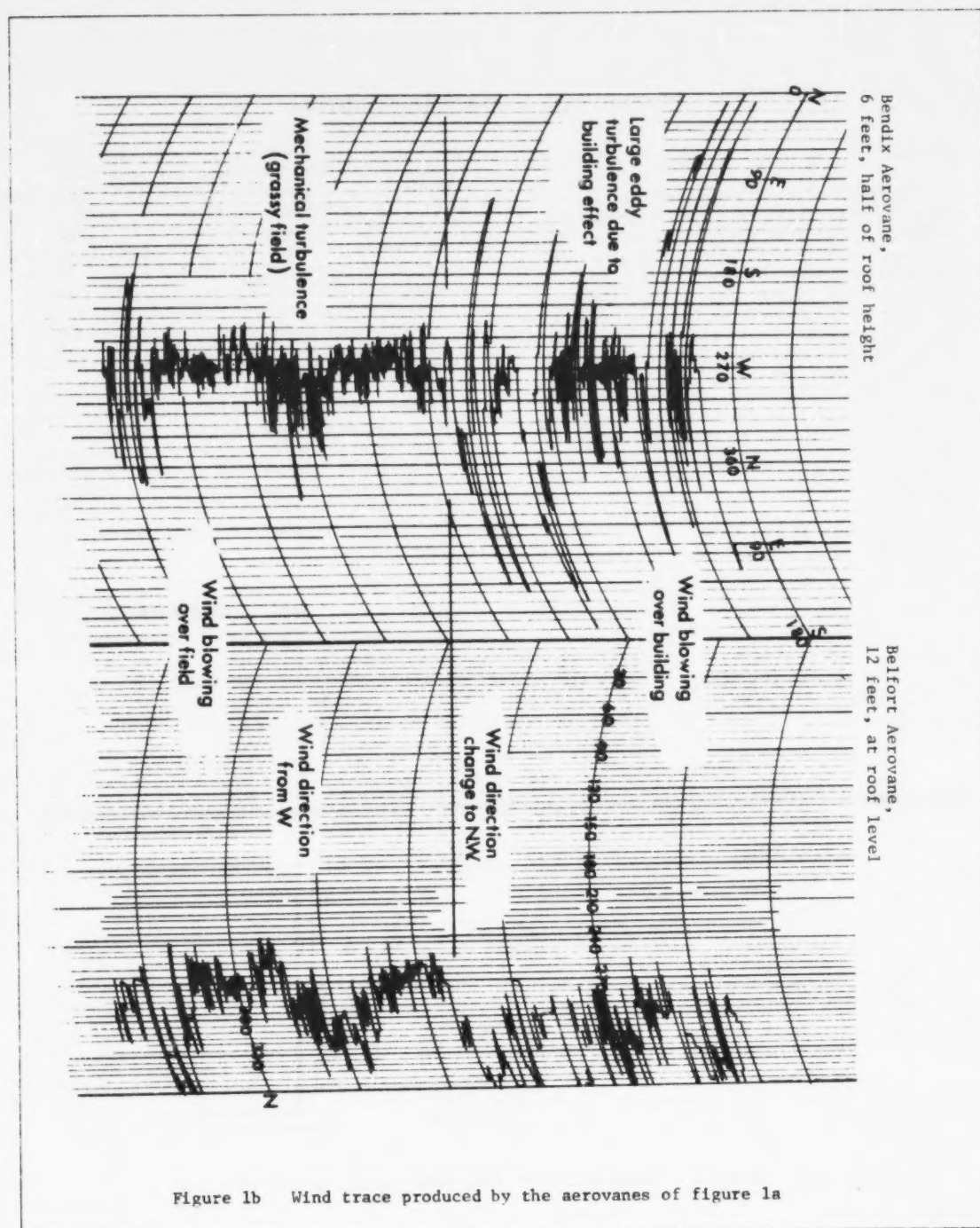


Figure 1a. Location of wind equipment that produced the traces of figure 1b

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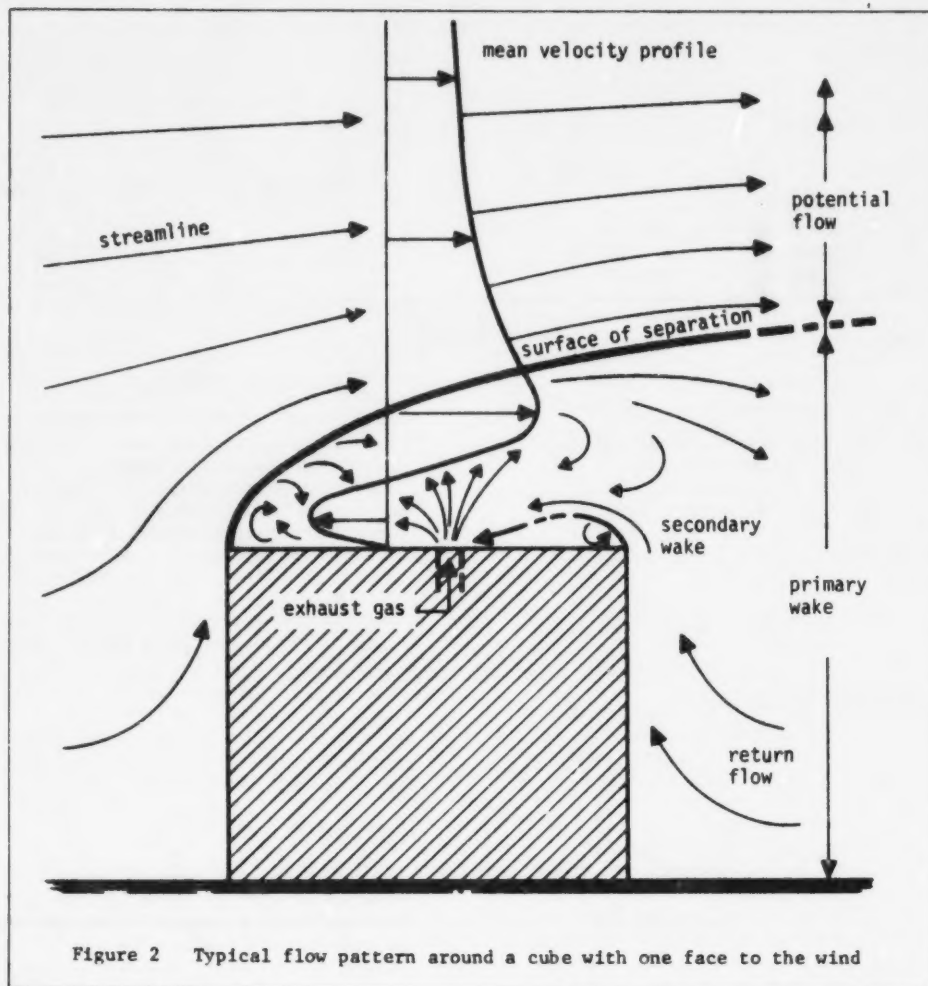


Figure 2 Typical flow pattern around a cube with one face to the wind

ANEMOMETERS AND WIND VANES

In recent years, an attempt has been made at standardizing the height above ground at which "surface wind" measurements will be taken. The World Meteorological Organization (WMO) and the National Oceanic and Atmospheric Administration (NOAA) have agreed on 10 meters for this standard height. Ideally the measurements would be taken over level, open terrain, but very rarely do these conditions exist in an air pollution survey area. What rules of thumb or guidelines can be followed if obstructions are present in the vicinity of the spot where wind measurements are to be taken?

Figure 2 illustrates a typical flow pattern around a cube that has one face normal to the wind flow. From Figure 2 several things can be noted:

- 1) The flow is disturbed on the up-wind and downwind sides of the obstruction.
- 2) The flow is disturbed above the building to a height of about 1 to 1 1/2 building heights above the roof.
- 3) Very near the roof of the building a reverse flow occurs.

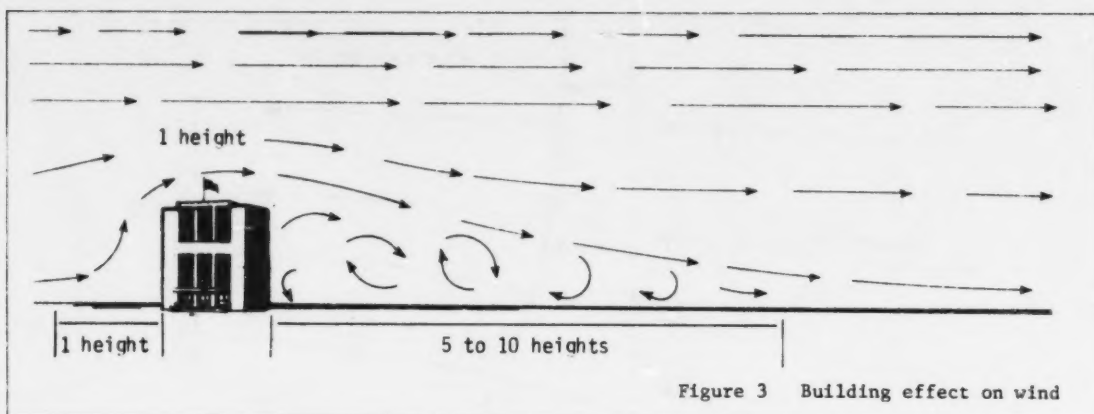


Figure 3 Building effect on wind

Figure 3 shows a more extensive view of the disruption in the ambient air flow around an obstruction. From Figure 3, one can formulate three rules of thumb for locating a wind system around an obstruction while keeping the sensor located in the ambient air flow:

- 1) The sensor must be located a distance upwind of the building equal to the building height.
- 2) If the sensor is to be located on the roof of the building it must be at least one building height above the roof.
- 3) The sensor must be located a distance of 5 to 10 building heights in the downwind direction.

These guidelines would apply most directly to a cubical obstruction standing by itself on open, level terrain. As the shape of the obstruction changes or as more obstructions become involved, the problem becomes much more complex. For example, suppose that it is desired to make measurements of the ambient air flow in the downtown area of a large city. Most probably the above guidelines could not be met because of the close proximity of the obstructions in a downtown area. A modification of these guidelines must be used. The sensor should be mounted on the roof of the tallest structure available, a distance above the roof determined by the proximity of taller buildings (using Guidelines 1 and 3), and the height of the building above the surrounding structures (utilizing Guideline 2). The exact height at which to locate the sensor would depend on the particular case.

In locating wind sensors in rough terrain or in valley situations, it will be necessary to determine if local effects such as channeling, slope and valley winds, etc., are of greatest importance, or whether flow above these influences is the parameter to be sensed. As in the urban situation, if the study centers upon elevated pollution sources, it may be desirable to avoid the local influences. However, if pollution from ground level sources is being emphasized, local influences may be of great importance. Remember that topographic influences such as hills, ridges, etc., produce flow patterns similar to those shown in Figures 2 and 3.

TEMPERATURE

As with wind sensors, thermometers are usually placed at a standard height above ground. This standard height has been set, by international agreement, at 1.25 to 2 meters (4-6.5 feet) above a grassy surface. Environmental considerations produce the following three rules of thumb for exposure of temperature sensors.

- 1) The sensor must be shielded from direct solar radiation.
- 2) The sensor must be well ventilated at a constant ventilation rate. (not less than 4-5 m/sec.)
- 3) The sensor must be uninfluenced by nearby features that might affect temperature.

If the sensor is of the thermocouple or thermister type, the aspirated shield of Figure 4 will fulfill the requirements of (1) and (2) above.

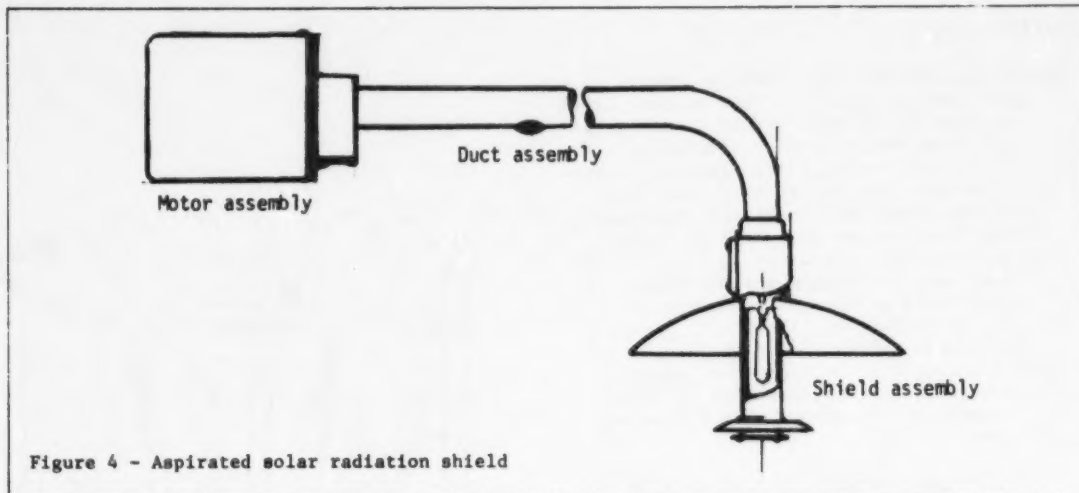


Figure 4 - Aspirated solar radiation shield

If a standard thermometer is to be exposed, the cotton region shelter of Figure 5 will fulfill requirement (1) above. Ventilation will be natural and therefore variable in rate so the requirement of rule (2) is not met exactly, but for standard thermometers, the error or effect is negligible.

If the shelter of Figure 5 is to be used, care should be taken to orient the door towards the north to eliminate solar heating of the thermometers while taking a reading. The thermometers should also be located as close to the center of the shelter as possible.

Requirement (3) above ensures that ambient air temperature is being measured, and not the temperature of a micro-environment such as the air very near the south side of a brick building or near an asphalt roadway or parking lot.

RELATIVE HUMIDITY

Since relative humidity is not only a function of the amount of water vapor in the atmosphere, but is also dependent on temperature, exposure criteria outlined for temperature should also be observed for relative humidity.

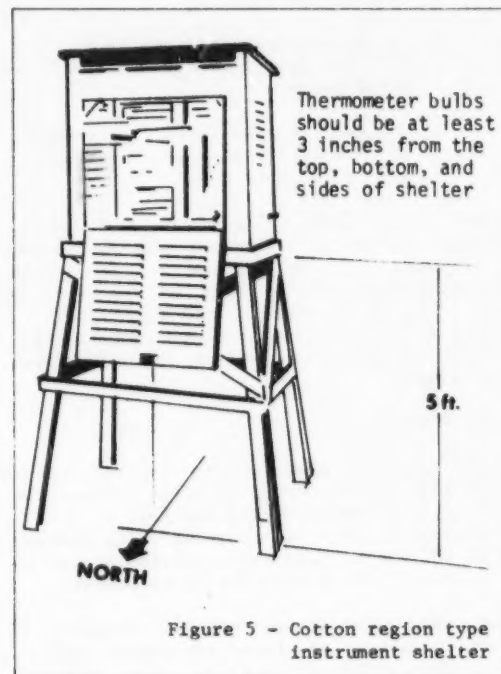


Figure 5 - Cotton region type instrument shelter

PRECIPITATION

The previous section describes the design and operation principles of rain gauges. Care must be taken in the exposure of a rain gauge to ensure that the collection efficiency of the gauge is not reduced. Wind and its associated turbulence are the two most important factors that would tend to change the collection efficiency of the gauge. If the wind blows the rain into the gauge on a slant, the collection area is changed and therefore the efficiency would be changed producing an error in the indicated rainfall. If considerable turbulence exists around the gauge, the rainfall itself will be disturbed, again producing errors in the indicated rainfall. These considerations produce the following guidelines:

- 1) The gauge should be free of overhanging obstructions.
- 2) The gauge should be a sufficient distance from obstacles to avoid local eddys.
- 3) The gauge should be sheltered from the possibility of high wind speeds at the gauge.

Ideally, all three criteria could be met if the gauge was located in a clearing in a woods or orchard where the diameter of the clearing is about equal to the height of the surrounding trees. A windshield, such as the one shown in Figure 6, can also be installed to reduce the distortion of the air flow around the gauge.

RADIATION

Solar radiation measurements require exposure that will insure no obstructions between the sun and the sensor during any part of the year, and in the case of total solar radiation (direct and diffuse) as clear a view as possible of the entire sky is necessary.

The measurement of net radiation requires that the sensor be placed far enough away from the earth's surface to receive terrestrial radiation over a representative area, yet not far enough from the surface to receive radiation from a thick air layer above the surface. For net radiation measurements, a height between 1 and 2 meters (3 to 6 feet) is generally recommended.

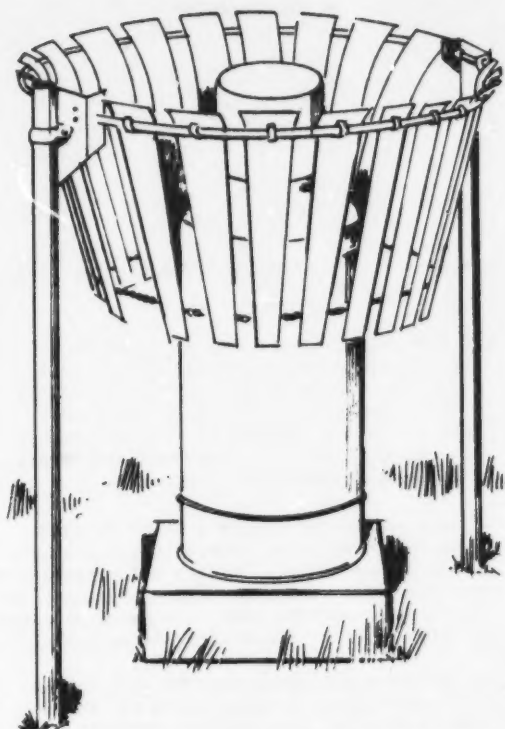


Figure 6 - Shielded rain gauge

Exposure of Instruments on Towers or Stacks

INTRODUCTION

In striving to meet the exposure criteria outlined in the last section, it is often necessary to mount meteorological sensors on towers or masts. Unless these sensors are mounted properly, errors will be introduced in the measurements due to the influence of the tower on the parameter being sensed. It is the purpose of this section to set forth guidelines to eliminate these tower induced errors.

WIND SYSTEMS

If a wind system (anemometer and vane) are to be mounted on top of a tower, little concern is needed as to exposure. If, however, wind equipment is to be installed on the side of the tower, precautions should be taken to ensure that the wind measurements are not

influenced by the tower. An analysis by Gill and Olsson (1967) has shown that the turbulence in the wake of lattice-type towers is moderate to severe, and that in the wake of solid towers and stacks is extreme, often with reversal of flow.

Another study by Moses and Daubek (1961) revealed that the air flow on the lee side of a tower may be reduced to about one-half its true value under light wind conditions and about 25% for higher winds (10-14 mph). The study also revealed that when the wind blowing toward the anemometer made an angle of 20 to 40° with respect to the sides of the tower adjacent to the anemometer, the measured wind speed exceeded the true wind speed by about 30%.

These studies illustrate the necessity of proper exposure.

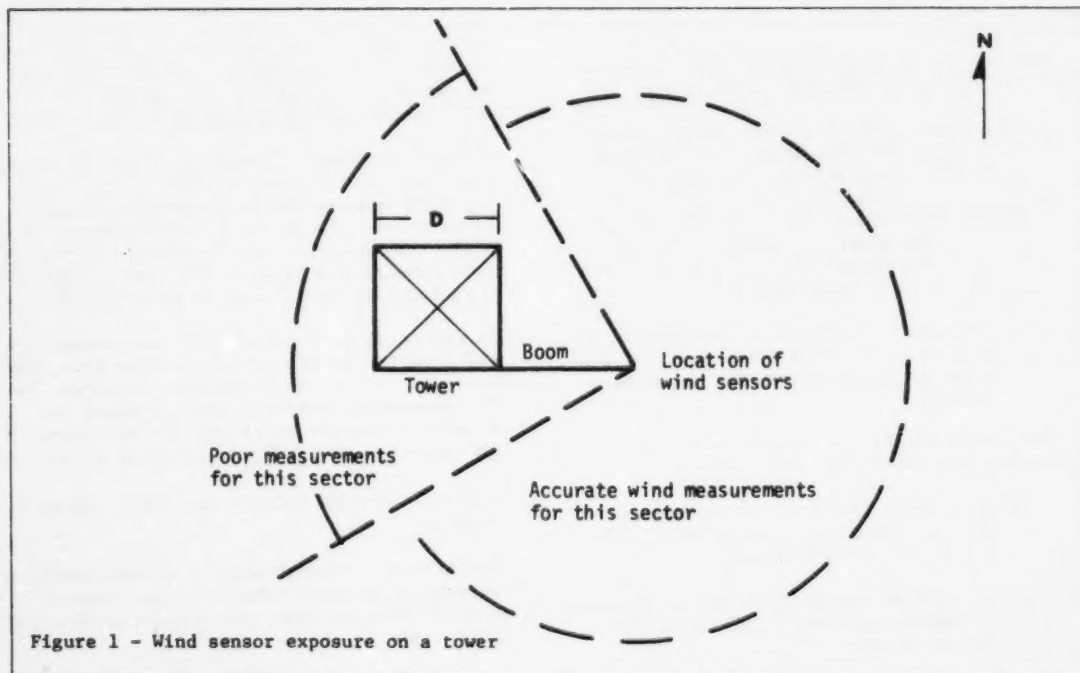


Figure 1 - Wind sensor exposure on a tower

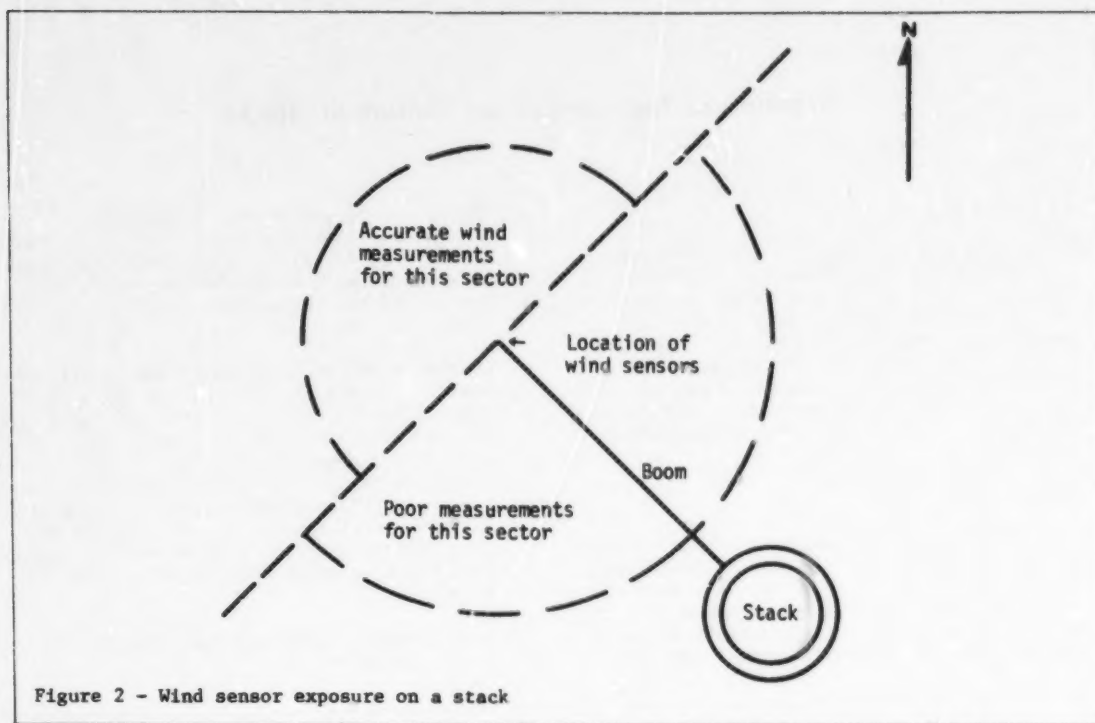


Figure 2 - Wind sensor exposure on a stack

Figure 1 illustrates the correct exposure of a wind sensor on an open tower. The following exposure criteria should be observed:

- 1) The boom should extend outward from a corner of the tower into the wind direction of primary concern.
- 2) The boom should place the sensor out from the tower a distance not less than the length of a side of the tower. (length D in Figure 1)
- 3) The wind sensors should be located at heights of minimum tower density, and above or below horizontal cross members.

If the above guidelines are followed, the following accuracies can be expected:

- 1) For a boom length of 1D, measurements of wind speed are true within $\pm 10\%$ for a 310° sector of arc.
- 2) For a boom length of 2D the wind speed is accurate within $\pm 10\%$ for a 330° sector of arc.
- 3) For these two arcs, wind direction is accurate to within approximately $\pm 5\%$.

With a boom length of 1-2D, wind speed and direction measurements within $\pm 5\%$ can only be obtained for a $240 - 270^\circ$ sector of arc. This is the case illustrated in Figure 1.

It has been found in practice that the maximum practical boom length is about 20-30 feet. If the wind sensors are to be mounted on very large towers (TV towers or fire look-out towers), the sector of arc yielding accurate wind measurements may drop to 180° due to the fact that the boom length may be less than 1D.

In any case, if accurate wind measurements are required for an arc sector greater than that produced by the above exposure criteria, it is recommended that two sets of speed and direction sensors be placed at 180° apart in the manner prescribed in the above guidelines.

EXPOSURE OF WIND SENSORS ON CLOSED TOWERS OR STACKS

Preferably, closed towers or stacks should not be used to support meteorological sensors. If a stack must be used, the following exposure guidelines should be observed:

- 1) The boom should place the sensor out from the stack a distance not less than 2 stack diameters.

- 2) Instruments should never be located within 2-5 stack diameters of the top of an active stack.

Figure 2 illustrates the correct exposure of a wind sensor on a stack. If the above guidelines are used one can expect accurate wind measurements (± 5 to 10% of true value) through an arc of only 180° as shown in Figure 2. As with towers, if accurate wind measurements through a full 360° of Azimuth are desired, it is recommended that two sets of wind systems be used. These two systems should be located 180° apart, and exposed according to the above guidelines.

TEMPERATURE SYSTEMS

Temperature sensors should also be exposed on booms out from the tower structure to assure that the temperature of the air sampled is not influenced by thermal radiation from the tower itself. Temperature sensors should never be mounted on stacks.

Booms for temperature sensors need not be as long as for wind sensors, but generally, both wind and temperature sensors are located on the same boom at about the same distance from the tower. The temperature sensors themselves must be shielded and ventilated as described in the previous section.

SPACING OF WIND AND TEMPERATURE SYSTEMS

Figure 3 illustrates a typical spacing of wind and temperature systems on a tower. Wind sensors are normally spaced at logarithmic height intervals (10, 20, 40, 80, 160 meters) because of the normally logarithmic change of wind speed with height.

- Temperature measurements should be made at close intervals near the ground, and at approximately equal intervals at greater heights as shown in Figure 3. A logarithmic spacing is not necessary since temperature profiles become approximately linear a short distance from the surface.

With both wind and temperature, provisions must be made for swinging or telescoping the boom in order to service the sensors. Provisions also must be made for orienting the wind vane correctly when the boom is in the service position.

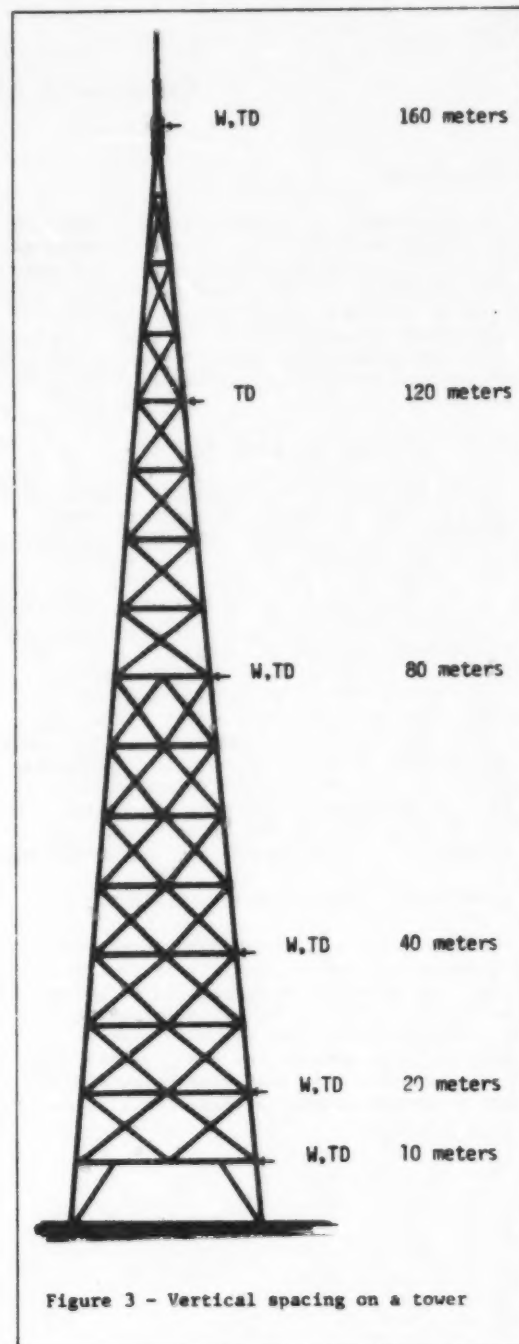


Figure 3 - Vertical spacing on a tower

Exposure of Airborne Instruments

INTRODUCTION

The measurement of meteorological parameters aloft may require the use of such devices as balloons, aircraft, rockets, etc. With many of these methods, surface-based receiving and recording instrumentation is necessitated. Therefore, a discussion of the exposure of airborne instruments must also include a discussion of the exposure of the surface-based support equipment.

EXPOSURE OF SURFACE BASED SYSTEMS

The measurement of wind aloft by balloon tracking may involve the use of radar or radio direction-finding equipment. Sites for radio and radar equipment should be on relatively high ground with the horizon as free from obstructions as possible. Of greatest importance to free balloon launchings is that there be no nearby obstructions to hinder the flight of the balloon. The operation of captive balloons (wiresondes) should be carried out only in open areas and never near power lines. Particular care should be taken to properly ground all captive balloon equipment and operations should be carried out only during periods of minimal atmospheric electrical potential. It should be noted that FAA authorization is necessary for most captive balloon operations.

EXPOSURE OF AIRCRAFT MOUNTED SYSTEMS

The main exposure problem associated with measurements from an aircraft is the fact that the sensors must be exposed to undisturbed air. Fixed wing propellor slipstreams and helicopter downwash must be avoided. For temperature measurements, engine and cabin heat must also be avoided, and a correction must be made for airspeed.

Vibration of receiving and recording instrumentation in the aircraft may also be a problem.

The following guidelines are suggested for exposure of aircraft mounted sensors:

- 1) On fixed wing aircraft, sensors are most effectively mounted on the wing-tips, forward of the wing not less than two feet.
- 2) On a helicopter, sensors are most effectively mounted on the forward tip of one of the skids, provided a forward speed of about 15 m/sec is maintained. This forward speed would project the downwash behind the sensor.
- 3) To reduce recorder vibrations, mountings of sponge rubber or plastic should be used.

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Exposure of Meteorological Instruments

- 1) Gill, G.C., Olsson, L.E., Sela, J., and Suda, M., "Accuracy of Wind Measurements on Towers or Stacks", Bulletin of the A.M.S., Vol. 48, No. 9, Sept 1967 pp 665-674
- 2) Moses, H., and Daubek, H.G., "Errors in Wind Measurements Associated with Tower-mounted Anemometers", Bulletin of the A.M.S., Vol. 42, No. 3, 1961 pp 190-194

Section Seven

DATA RECORDING

**Recording Instruments - An Outline of Basic Design
Characteristics for Meteorological Applications**

Meteorological Data Telemetering

Recording Instruments - An Outline of Basic Design Characteristics for Meteorological Applications

Daniel A. Mazzarella

I. Recorder Types, Basic Designs

A. Mechanical

1. Drum drive, rectangular chart (Cartesian)
2. Disc drive, circular chart (Polar)
 - a. Filled systems

B. Electrical/Electronic

1. Galvanometric

- a. Direct writing, strip chart
 - (1) D.C. - milliammeter, voltmeter, ammeter, microammeter
 - (2) A.C. - milliammeter, voltmeter, ammeter, microammeter
- b. Light-Beam recording, strip chart

2. Null-Balance, servo-operated type

- a. Potentiometric
- b. D.C. Bridge
- c. Force-balancing servo type

3. Event/Operations/Impulse

4. Digital

5. Other recorders and specials

- a. The X-Y recorder, either null-balance or galvanometric light beam
- b. Sweep-balance recorders (facsimile)
- c. "Receiver" recorders (wind direction)

6. Oscilloscope-Camera recorders

II. Mechanical Recorders

A. Drum type, rectangular charts

1. Designs: temperature, humidity, pressure, rainfall, sunshine, etc.
 - a. Options in design
 - (1) Number of pens - 1 to 3
 - (2) Chart drives - spring-wound (8-day, 31-day), battery-powered
 - (3) Gears - hours, days, weeks, month, 168 hour
 - (4) Ink - color, drying time, temperature range

B. Disc type, circular charts

1. Portable and permanent
2. Filled systems
 - a. SAMA (Scientific Apparatus Manufacturers Association) Classification
 - (1) Class I
 - (2) Class II
 - (3) Class III
 - (4) Class V

C. Special

1. "Mechanical Weather Station" - springwound, battery-powered

III. Electrical/Electronic

A. Galvanometric

1. Direct writing, (D'Arsonval movement), spring-restored pen motor
 - a. Continuous, curve-tracing
 - (1) Critical damping
 - (2) Source resistance, galvanometer resistance
 - b. Periodic, chopper-bar recording

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Type	Approx. Channel Size	Typical Frequency Response		
		Full Scale	Reduced Scale	Maximum
CHOPPER BAR	2"	---	---	1
CURVE TRACING, SPRING RESTORED	4.5"	2 Hz	10 Hz	100 Hz
SERVO LOOP				
OSCILLOGRAPH	5"	10 Hz	60 Hz	300 Hz
	1.5"	60 Hz	200 Hz	1,000 Hz
LIGHT BEAM				
OSCILLOGRAPH	3"	1,000 Hz	4,000 Hz	5,000 Hz
UV BEAM				
OSCILLOGRAPH	6"	13,000 Hz	25,000 Hz	25,000 Hz

2. Direct writing, recording oscillographs
 - a. Servo-loop feedback of Brush Instrument Company
 - (1) Position feedback pen motor
 - (2) Forced-fluid writing
 - (3) Rectilinear recording
 - b. Electrodynamic, direct-writing and rectilinear of Massa Instrument Company
 3. Light beam recording oscillographs, optical systems
 - a. Minor reflection on photosensitive film or paper
 - b. Light beam servo recorder
 4. Advantages of galvanometric recorders
 - a. Economy
 - b. Sensitivity
 - c. Frequency response
 5. Frequency response of galvanometric recorders (see comparison chart-above)
- IV. Null-Balance, Servo-Operated Recorders
- A. Potentiometric
 1. Definition (potentiometer vs. variable resistors)
 2. Advantages
 - a. Sensitivity in microvolt range
 - b. Cancellation of input signal makes lead length considerations unimportant.
 3. Disadvantages
 - a. Speed of response limited to .25 sec. full scale
 - B. Frequency response limited to 1 Hz. Full scale on a 10" chart; at reduced amplitude, 6 Hz.
 - C. The D. C. bridge in a null-balance, servo-operated system
 - a. Temperature
 - b. Temperature-difference
 - D. Potentiometric recorders of the force balancing servo type
 - a. Frequency response full scale from 5 Hz to 30 Hz; at reduced amplitudes from 10 Hz to 60 Hz.
- V. Event/Operations/Impulse Recorders
- A. Principle - switch closure
 1. Event recorded on moving chart
 - a. solenoid-operated pen
 - (1) bi-polar pens
 - b. hot stylus
 - c. electrosensitive paper
 - d. stylus, pressure sensitive paper
 - B. Applications
 1. Wind passage
 2. Wind direction
 3. Rainfall
 4. Time markers
 - C. Analog-Event recorders
 - D. Event-Time totalizer
 - E. Special event recorders
 1. Solenoid-sequencing of channels
 - F. Power requirements of event pens
 - G. Channels
 1. 10 are common, up to 20 solenoid operated/case
 2. Available to 450 in electrosensitive technique

VI. Digital Recorders

A. Definition - printers of numerical (discrete) data

1. Typewriters - manual, electrical, high speed
2. Digital printers
 - a. Electromechanical
 - b. Electronic

B. Digital Printers

1. Printing Impulse Counters - Sodeco
2. Digital Printer - a device which accepts and records compatible signal from digital instruments or transducers; it has no measuring circuit.
 - a. Suppliers: Esterline Angus, Hewlett Packard, Digitek, Clary, Systron, Donner
 - b. Signal Sources: digital clock, digital transducers for temperature, pressure, etc., shaft encoders, position transducers, digital scanners.
 - c. Analog to Digital Signals - from the Digital Voltmeter (DVM), with output in BCD format.
3. Data logging and the digital printer
 - a. Components - sensors, DVM's, controls module
 - b. Typical data loggers with digital printers
 - (1) Esterline Angus
 - (2) Teledyne Geotech
 - (3) Climet
 - (4) Bendix

VII. Other Recorders and Specials

A. The X-Y recorder

1. Recording technique either null-balance or galvanometric light beam
2. A plot of dependent variable against independent variable
 - a. X is the pen signal
 - b. Y is the chart signal

B. Sweep-balance

1. Principle - the chart is marked at the instant that the amplitude of a sweep (ramp) signal matches that of the input signal.
2. Combines the sensitivity of potentiometric recording with a high speed response.

3. Applications include facsimile recording of weather maps.

C. "Receiver" recorders, special recorders.

1. Reference is to synchro receivers used in wind direction sensors.
 - a. Bendix designs
 - (1) 180 deg. reversal, cam, event pen
 - (2) 540 deg.
 - b. Belfort design
 - (1) 540 deg. - 2 pen

VIII. Oscilloscope - Camera Recorders

A. Cathode ray tube with camera recording

1. Applications - for events with frequencies of 5,000 Hz and above.

IX. The Terminology of Recorder Specifications

A. Dynamic Characteristics

1. Critical Damping - In the majority of applications, it is desirable for the pen of a recorder to respond to a step function in the shortest possible time, but with no overshoot. This condition is called critical damping; it is the borderline between over-damping and underdamping.
2. Frequency Response - That portion of the frequency spectrum which can be covered by an instrument within specified limits of amplitude error.
3. Overshoot - In an underdamped recorder, overshoot represents the amount of pen travel beyond the final steady step function.
4. Rise Time - The length of time for an instrument to respond from one value to another after a step input, e.g., 0.2 sec. to reach 99% of the final value. Rise Time, like Response Time, is ambiguous. Response Time, when expressed as a Time Constant - the time required to reach 63% of a final step change value - is more significant.
5. Step Response - This is sometimes identified as Span Step Response. It is the maximum time required to respond to a full span step signal. "Slewing Rate", which is the maximum speed of pen travel

for a full span, is sometimes used instead of step response of a recorder.

6. Time Constant - The length of time required for the output of a device with first order characteristics, to change to 63% of its final value, after a step change.

B. Electrical and Mechanical Characteristics

1. Accuracy - A term used to describe the total performance of a recorder in terms of the limits of the inaccuracies for the components. Accuracy is usually expressed as a percent of span, exclusive of the sensor accuracy. A recorder with a span of 10mv and a rated accuracy of .25% is accurate to $\pm .025\text{mv}$ anywhere on scale.
2. Analog - An adjective which, when used in reference to instruments, has come to mean "continuous", in contrast to Digital which means "discrete".
3. Common Mode Interference - A form of interference which appears between any measuring circuit terminal and ground. Also called a Common Mode Signal.
4. Common Mode Rejection - A measure of how well a differential amplifier in a recorder ignores an interference signal which appears simultaneously and in phase at both input terminals. It is usually expressed as a voltage ratio of the common mode signal required to give the same recorder deflection as the input signal. Often, it is also stated in the db equivalent of the given ratio at a specified frequency, e.g., 120 db (1,000,000:1) at D.C.; 100 db (100,000:1) at 60 Hz A.C.
5. Dead Band - This is the range through which the measured signal can be varied without a response from the recorder. It is expressed in percent of span.
6. Elevated Zero Range - If we assume a recorder has a range of 0 to 100, an elevated zero range might be represented by -20 to +80, -50 to +50, or -100 to 0, where the zero value of the meas-

ured signal is greater than the lower range value.

7. Floating - The condition of a device or circuit that is not grounded and not tied to any established potential.
8. Impedance - An indication of the total opposition that a circuit or device offers to the flow of alternating current at a particular frequency. It is a combination of resistance "R" and reactance "X", at a designated frequency, all expressed in ohms; $|Z| = (R^2 + X^2)^{1/2}$. It is important to differentiate between input impedance (the recorder) and source impedance (the source). Also important is a differentiation between impedance and resistance, the latter relates to D.C. circuits.
9. Range - A statement of the upper and lower limits between which an instrument's input may be received and for which the instrument is calibrated. The spread between two established points within the Range is the Span, e.g., Range -20 to +80; Span 100.
10. Repeatability - The closeness of agreement among a number of consecutive measurements by the instrument for the same value of the measured signal under the same operating conditions. It is usually expressed in percent of span, representing the maximum deviation from the mean of corresponding points taken from repeated tests.
11. Sensitivity - The property of an instrument which determines scale factor. Frequently, this term is shortened from "maximum sensitivity", or "minimum scale factor" with which an instrument is capable of responding.
12. Source Resistance - This is the resistance presented to the input of a device by the source, which may be a sensor for wind, temperature, humidity, etc. Impedance, which is more complex, is not to be confused with source resistance.
13. Suppressed-Zero Range - A range in which the zero value is less than the lower range value. Zero does

not appear on the scale, e.g., 20 to 120, 50 to 150.

14. Thermocouple Reference Junction - When the purpose of a recorder is to measure temperature by means of a thermocouple, compensation is automatic.

15. Threshold - The smallest change in input which will result in a measurable change in the recorder.

16. Zener Diode Reference - A solid state power supply which operates from A.C. and which furnishes a precise, stable, and highly isolated D.C. potential to a potentiometer circuit. This reference source eliminates the need for standard (mercury) cells and the standardizing mechanism, used in many older recorders, making instrument maintenance much easier.

17. Zero Offset - When a recorder is supplied with a zero offset adjustment it is possible to elevate the zero from the base line. Instead of reading .0 to 25mv, the span can be changed to -5 to +20 mv, or some other span within the 25mv range.

18. Zero Suppression - A technique of bucking out part of an incoming signal (the static component) so that the rest of the signal (the dynamic component) may be amplified and expanded on a recorder chart.

X. Options, Choices, and Variations in Recorder Selection

A. Common to both galvanometric and potentiometer types

1. Case style size, construction
 - a. Portable: panel, wall, relay-rack mounted
 - b. Illumination
 - c. Chart drive
 - (1) electrical, springwound
 - (2) chart speeds, automatic, manual, change gears
 - (a) standard vs. rapid feed
2. Charts
 - a. Size, number of channels
 - b. Writing method: capillary ink, forced fluid, pressure sensitive, etc.
 - (1) Curvilinear vs. rectilinear
 - (2) Event pens

- c. Length of chart roll, time markings, electrical units, eng. units

3. Electrical characteristics
 - a. Amplitude response, Frequency response
 - b. Linearity
 - c. Input impedance (resistance)
 - d. Threshold

B. Common to potentiometers

1. Single or multiple curve tracing vs. multiple (sequential) dot printing
 - a. Trace and dot identification, color, number ("Cleertrend", "Ident-a-point")
2. Range switching: manual vs. automatic
3. Retransmitting slidewires
4. Integrators

XI. Meteorological Applications for Recorders

A. Measurements

1. Wind
 - a. Direction
 - b. Speed
2. Temperature and temperature-difference
 - a. Resistance element (RTD) - platinum, copper
 - b. Thermistor element
 - c. Thermocouple element
3. Humidity
 - a. Relative humidity
 - b. Dew Point
 - c. Dry bulb - wet bulb
4. Pressure
5. Precipitation
6. Solar Radiation

B. Records

1. Sample charts for wind, temperature, humidity, pressure, precipitation, and solar radiation

XII. Miscellaneous

A. Chart viewers

1. Esterline Angus - supplier
 - a. hand operated for 6" chart
 - b. motorized for widths to 12"
2. Rustrak
3. Pittsburgh Engineering Products Co. ("Easi-Vue")

Recording Instruments

4. Gerber Scientific
5. Nuclear Supply and Service Co.
("Chart Editor")

B. Charts - suppliers

1. Graphic Controls
2. Judson Biglow
3. Recorder manufacturers
4. Gubelman

C. Inks

1. Slow feed
2. Rapid feed
3. Color
4. Temperature Range
5. Suppliers

Meteorological Data Telemetry

Charles W. Barbour

INTRODUCTION

This section is intended to provide a brief understanding of some of the essentials of meteorological data telemetry systems; the choices that one can make in such systems, their general characteristics and approximate ideas of relative costs of various components of the systems. No effort is made to discuss extensively the theory of the various telemetry systems, but rather to give an overall view which may assist in making judgments as to how best to telemeter a particular piece of information.

To begin with, let us define telemetry. Perhaps the shortest definition is that to telemeter is to "measure at a distance". First, at the remote point, a transducer is needed, a device which converts the physical quantity being measured into a signal (usually an electrical one) so that it can be more conveniently transmitted. Then, a connecting link is needed between the location where the measurement is being made and the point where the signal may be read or recorded. This link can be either an electrical circuit, a radio carrier frequency, or in some cases, even a light beam or sound path. Telemetry systems are available in many different types of modulating techniques as well as transmission mediums. The telemetry art, of course, has been used for a great many years for remote measurement, and has been carried to probably its ultimate refinement in the course of the space data communication program as well as the missile development programs. In the military and aerospace fields, great precision of measurement has been obtained using highly efficient systematic methods which economize greatly on communication bandwidth requirements, while at the same time providing optimum accuracy capabilities. The meteorological field, in general, does not require this degree of sophistication and so this course will be limited to the more conventional forms of telemetry systems that might be encountered in actual experience.

1.0 TYPES OF TELEMETRY SYSTEMS

The first, and probably the simplest form of modulation, is what is termed direct amplitude modulated telemetry. Here, the basic system consists of a direct hard-wire transmission line between the sensor and the remote display or recorder. In other words, nothing

more than a sensor at one point and wires connecting that sensor to a meter at a remote point. The remote point, of course, may be some distance away, depending upon the system. This system has the advantage that it is essentially simple. Very little technical refinement exists in it, and it is easy to understand and organize. However, it has numerous limitations that make it useful really in only special situations.

Amplitude modulated telemetry, first of all, requires DC coupled dedicated telephone or other type transmission lines. In other words, one must have a direct link between the sensor and the display device. The system accuracy deteriorates as the transmission distance increases because line losses directly effect the results. In other words, if the line has a high series resistance inherent in it, it is going to affect the accuracy in the reading at the remote point, and usually that accuracy or that error will be directly dependent upon the length as well as other properties of the line. In general, the accuracy of such a system is poor. Usually, it is considered to be in the order of 10 to 20%, although in special cases, it is possible to do somewhat better, but with very restricted facilities. The system is very vulnerable to noise pickup on the line. Bursts of noise that occur on long lines can seriously affect the readings at the receiving end of the line. Direct amplitude modulation is very inefficient in its use of the line bandwidths, which means effectively that it is expensive in terms of communications network facilities. Furthermore, it is essentially a slow speed system and is unable to handle data rates which are sometimes encountered. Lastly, the system is not computer compatible and the data at the receiving end requires further processing before a computer can be used to digest it.

Another type of system is known as Frequency Modulated Telemetry (FM or FM/FM). A typical system block diagram is shown in Figure 1. Here the sensor outputs are used to control the frequency of a series of oscillators whose output is then transmitted over wire lines or a radio-link. In other words, an AC voltage of varying frequency is transmitted. At the receiving end, a frequency discriminator, a device that measures the frequency and develops a voltage proportional to it, translates the frequency modulation into a DC or AC output essentially identical to the

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Meteorological Data Telemetering

original sensor output. The advantages of this type of system are that it is still relatively simple, and yet, is easily interfaced with existing telephone or radio communication networks. The fact that the voltages to be measured are converted into a series of varying frequencies means that it is easy to communicate those measurements to a remote point, since most of our communication networks utilize AC voltages for communication. The design of the voltage control oscillators used at the transmitting end, as well as the discriminators used at the receiving end, has been carried to a fine state of development, and these devices are now readily available in various levels of accuracies and sophistication, so that it is relatively easy to put systems together utilizing these devices.

The system limitation is principally that the system depends upon the frequency stability of the voltage-controlled oscillator and the frequency stability of the remote discriminator for its accuracy. Both of these devices have inherent temperature coefficients which have to be carefully controlled so that basically the accuracy is limited by the temperature characteristics of the system. Accuracy is usually limited to something on the order

of 2-5% for practical installations, although in the more sophisticated installations, accuracies of the order of 1% are sometimes obtained. Although the system makes much better use of the available bandwidths, its efficiency is still not as high as that obtainable with some other techniques that we will discuss later. The system is not computer compatible without extensive processing of the received measurement, and this is an important aspect of the FM telemetering system that must be recognized. Even though the individual elements of the system are relatively simple, the number of these elements required to make up a system become quite significant in actual practice and the cost of an FM telemetering system can sometimes be unduly high if many sensor measurements are involved.

A variation on the FM telemetering system that stems from the missile development work is called Pulse Duration Modulation Telemetering, PDM or PWM for short. This type of system is similar to FM except that the sensor outputs control the length of a pulse, which then is transmitted as an AC voltage burst of a single frequency. At the receiving end of the system, the burst is de-

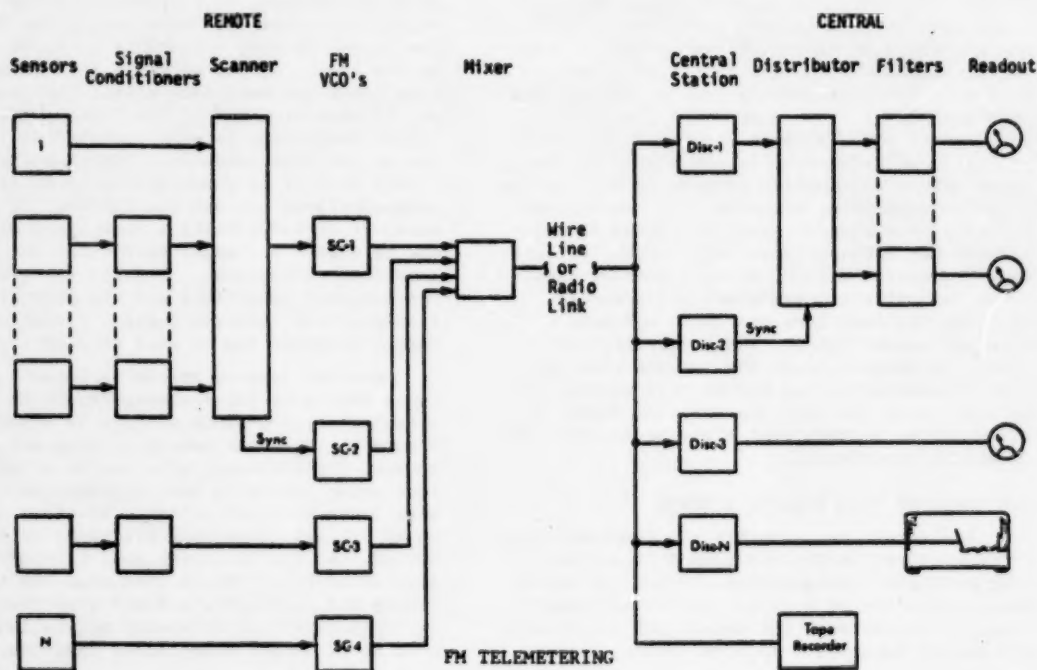


Figure 1

tected and a reproduction of the input pulse results. The pulse length is then measured, usually by digital techniques, to ascertain the original sensor signal. The advantages of this system are similar to those of the FM system. The basic building blocks of the system look quite similar, in that instead of voltage-controlled oscillators, one now has pulse width controlled modulators; and that instead of FM discriminators, one now has pulse width measuring discriminators to measure the length of the pulse on each individual measure. The system block diagram would appear very similar to that of the FM telemetering system.

The limitations of the system are similar to those of the FM system in that the basic accuracies are dependent upon the time duration stability of the pulse width modulator and the pulse width measuring system at the receiving end, and this stability is a function of the temperature characteristics. Accuracy with this type of system is usually limited again to approximately 2-5%, although usually it is capable of being somewhat more accurate than the FM system, and 3% accuracy is considered attainable. Again, in special cases, one can get accuracies of the order of 1%, perhaps even slightly better under very special circumstances, but these improved accuracies take great care in set-up and control of the measuring environments. The efficiency of the bandwidth utilization of a PDM or PWM system is similar to that of the FM system. It is essentially a medium bandwidth utilization type system. The output pulse of the PDM system has to be measured in one way or another, and in order to make this compatible with computers, that measurement must be made using digital techniques, so that the system isn't generally directly computer compatible.

The third, and possibly most important form of modulating system, and the one which we will concentrate most of our attention on, is called the Pulse Code Modulated or the PCM type system. Here, the sensor outputs are sampled and converted via an A/D converter to a binary code representing the instantaneous sampled amplitude. The binary code is then transmitted either directly or via frequency shift keying or FM-ing, and the received code can be entered directly into a computer or recorded for later use. The transmission takes place in the form of an actual binary code representing the quantity.

The advantages of this type of system are actually many. The signals are easily interfaced with the transmission lines and/or data logging equipment, because it is very easy to

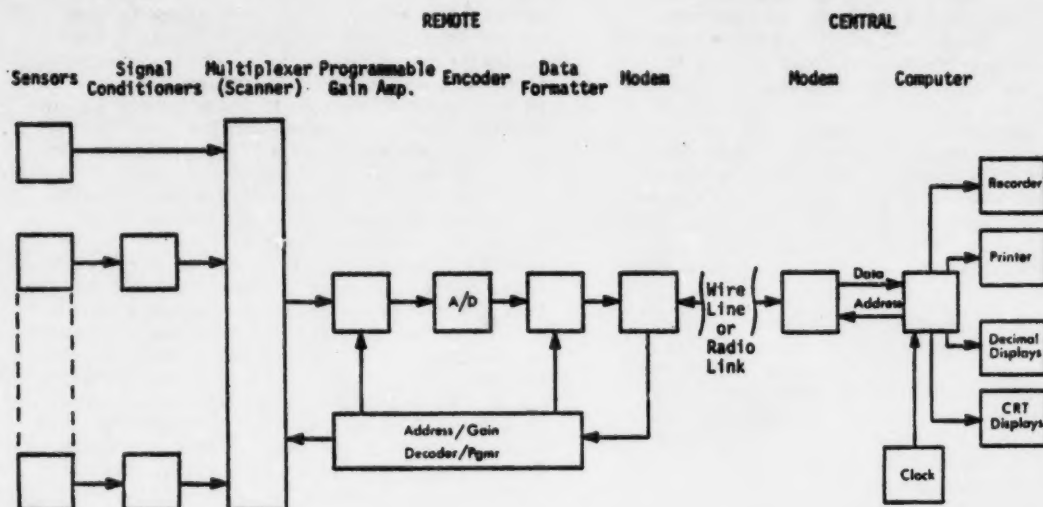
communicate simple pulses in sequence. The accuracy is not affected by transmission characteristics because the information is contained in the sequence and grouping of the pulses rather than in their amplitude or width or other peculiar property of the pulses. It is very easy to reproduce these pulses and reinforce them with booster amplifiers, if necessary, along the lines without any deterioration in accuracy as a result of such amplification. The accuracy is not affected by the transmission, only by the basic A/D converter, and accuracies of 0.1% to 1% are readily attainable. Furthermore, these accuracies are independent of the properties of the link. This system uses the available bandwidth most efficiently, so from the standpoint of communications' cost when properly applied, the PCM system will result in lower operating costs. As previously mentioned, the system is essentially invulnerable to line noise and line losses if proper precautions are taken to discriminate against false pulses, which is easily done. Perhaps the biggest advantage of all is the fact that the output is directly computer compatible, since all digital computers operate with some form of a binary code input.

The disadvantages are relatively limited in that perhaps the biggest difficulty is that the system requires a more extensive technical background in order to implement it in the most efficient way. This knowledge is becoming more commonplace, however, and it may not be a problem very much longer, because people are becoming more acquainted with digital techniques and generally understand how to utilize them more readily than they have in times past. A block diagram of the typical PCM Telemetering System is shown in Figure 2.

2.0 PCM SYSTEM ORGANIZATION

A PCM Telemetering System, as well as other types of systems, in general, consist of a central station and one or more remote stations connected via a wire line or radio-link, depending upon the type of installation. The central and remote stations may operate in either of two basic modes of operation; one, termed repetitive or asynchronous, updating where the control of the updating is maintained at the remote stations; i.e., the remote station initiates the transmission of a new message based on its own clock frequency; and the second, random access or polled operation.

The advantage of the first type of system is that it somewhat simplifies the hardware at the remote station, in that only a simple clock is necessary to initiate periodic



PCM TELEMETERING

Figure 2

updating. The disadvantages, however, are relatively severe in that although the system is simple, it is usually wasteful of the transmission and the recording medium at the central station, because data is being transmitted when it is not necessarily wanted by the central station. Thus, when the repetitive data is coming in, it may be redundant, and not particularly useful at that time, but the system has no way of knowing this, and therefore, continues to transmit information when it isn't needed. A further disadvantage is that it is awkward to systematize the data at the receiving station since it may be coming in from several remote stations at the same time. The time correlation of the data is difficult because it is initiated by independent clocks at the remote stations and it is usually necessary to transmit chronological time periodically in order to correlate data from different stations.

The second and preferred mode of operation is termed "Random Access" or "Polled Updating". In this type of system, the central station controls the timing of a data transmission by periodically transmitting a signal to the remote station, commanding it to update its particular readings. The central station records this set of readings, and then proceeds to poll the next remote station, and the operation continues on a periodic basis.

ation continues on a periodic basis.

The advantages of this type of system are fairly obvious. The data is fully systematized, and is readily computer compatible, because the central station computer maintains its own program to poll the outlying remote stations at the time that it wants the data. Time correlation is virtually inherent because the timing is established by the computer. It knows the time at which it requests an updating, and it is quite possible to add additional time measurement codes to account for any lost time that might be of importance. The system is readily expandable. In other words, it is easy to add additional outlying remote stations at will without completely upsetting the systemized recording of the data. Furthermore, the system has a predictable utilization of the transmission medium, and can realize maximum economies in tariff rates for wire lines or radio links.

The PCM Telemetering System block diagram, Figure 2, shows the components that go to make up a typical system. The sensors can be any of several different kinds, and depending upon their output, the system may incorporate signal conditioners which are devices to alter their signal voltage and character in such a way that it is compatible with the in-

put requirements of the A/D converter. Following the signal conditioner is what is called the multiplexer or scanner. The multiplexer is basically a time-sharing switching arrangement, which connects the A/D converter systematically to, first, one sensor output, then to the next. The output of the multiplexer is coupled, in this case, through a programmable gain amplifier, to condition the particular sensor signal level to the proper level for the A/D converter. The digital data output of the A/D converter, or encoder, then goes into a data formatter, which assembles the digital information in a prescribed format that the central station can recognize, and, in turn, interpret with regard to the start and end of a given message. The remote station includes a decoder programmer, which is the station controller, or the device which initiates the readout updating the measurements. The programmer operates either on a repetitive or polled basis. Polled operation is initiated by decoding and recognizing a code transmitted from the central station. The modem at the output end of the station is a device which couples the signals generated at the remote station to the communications facility, be it either a wire line or a radio-link. The transmitting modem may take several different forms, depending upon the details of the communication network, and frequently is a device that is provided as a standard interface by the company providing the communications link. The modem usually provides frequency shift keying to generate an AC output signal at a level and frequency that is compatible with the transmission system characteristics.

The central station consists of a corresponding receiving modem, which accepts the data coming from the transmission line and converts it, from a frequency shift-type signal, to a series of pulses that can be directed immediately into a computer or other digital device. The computer, of course, controls the timing of the system operation using an internal clock, and processes the incoming data in a systematic way, in accordance with its own built-in program. The computer operations include scaling of the data, time correlation of the data, addition of identifying headings to the data for the particular remote station or sensor, and outputs the data in suitable formats, to drive various types of display or readout devices, such as a tape recorder or a line printer, if immediate hard copy readout is desired. The computer may operate decimal illuminated display indicators, allowing an operator to observe particular readings. In the case of extremely high data rates, a cathode-ray tube display may be utilized to present numeric readout direct from the outlying remote stations.

3.0 PCM SYSTEM COMPONENTS

It will be informative to consider the characteristics of the system components in greater detail. The sensors are selected for the particular measurement involved, and their characteristics are familiar to the meteorologist.

Signal conditioning, in general, is easily categorized into a number of different functional requirements. First is the problem of amplification, which can be accomplished with fixed gain amplifiers on each channel, or a programmable gain amplifier, as mentioned previously. The programmable gain device permits one to amplify each selected sensor output to a predetermined full scale level before the A/D converter encodes the signal. In other words, this type of amplifier can be used to normalize the outputs of all sensors using a single amplifier with controllable gain settings, instead of a separate amplifier on each sensor. Obviously, the time shared amplifier can save a good deal in cost of equipment, as well as reliability of operation.

In some cases, amplification is not necessary; in fact, just the opposite may be required. That is, the sensor output may require attenuation or voltage dividers to drop the level and make it compatible with the general system operating level. These devices are also a form of signal conditioning.

Yet another type of signal conditioning is involved when it is necessary to convert an AC voltage output from a sensor to a DC signal that can more readily be sampled and encoded within the system. AC to DC conversion is frequently accomplished by devices that are called phase sensitive demodulators. These are special types of rectifiers, which permit sensing polarity of the voltage as well as its magnitude. In some cases where accuracy permits, it is possible to utilize simple AC rectifiers whose output will be a DC voltage proportional to the magnitude of the AC signal.

Some sensors require special balanced type amplifiers or input bridge circuits. For instance, strain gauges require some means to excite the strain gauge, and in turn, to couple the output reading from the gauge into the sampling PCM system. Strain gauges, and for that matter, thermocouples, are usually a special problem, requiring more expensive differential type amplifiers and/or balanced input bridges to provide the necessary interface. Thermocouples are a serious problem, in that most frequently their output is just a few microvolts (or perhaps millivolts) and it is a difficult matter to amplify these low

level signals to a sufficient high level to pass them through the system. Thermocouples, although very frequently used for accurate measurement of temperature, are becoming obsolete, and are being replaced by thermistors or solid state sensors that develop high level output signals directly.

Another signal conditioning function is the linearization and scaling to engineering units of the various input measurements. Occasionally, this function is performed at the remote station; however, doing it at this location is usually a very expensive way of handling the problem. The more economical way to approach linearization and scaling is to utilize the computer at the central station to accomplish the operation on a channel by channel basis in accordance with a fixed program built into its memory. A computer is normally capable of doing this at a high rate of speed, with a high degree of accuracy, and without the complex temperature problems that are usually involved in trying to perform this function at the remote stations.

It is helpful to present typical costs for signal conditioning as a part of a total system package. The costs presented are higher than those for individual components because they include mounting hardware and interconnection wiring within the system. The programmable gain amplifier is typically a \$300 to \$500 item. Fixed gain amplifiers run \$150 to \$500 per input. The \$500 cost applies to those cases where differential type inputs such as thermocouples or strain gauges are involved. It is advisable to avoid differential type signals if possible, and utilize single ended type sensor outputs instead to minimize the amplifier problem. Attenuators, or voltage dividers, are typically of the order of \$10 to \$20 per input. AC to DC conversion ranges from \$50 to \$150 per input. Balanced input bridges and strain gauge type excitation devices are approximately \$50 to \$100 per input, in addition to the above-mentioned amplifier costs.

The next major element of the system to be discussed in more detail is the scanner, or multiplexer. Several alternative approaches to this time shared switching device are available. The simplest is the familiar stepping switch, or motor-driven commutator. This type of device has been used for many years and is quite satisfactory for slow speed sampling of many inputs. In general, switching speed is limited to something on the order of 1 to 10 inputs per second. Another type of switch that is frequently used is what is known as a reed relay. The reed relay is a miniature switch on each input usually opera-

ted by a small magnetic coil. These devices are quite economical and permit a maximum of approximately 100 to 200 inputs per second to be sampled. The third type of scanner is a solid state switch; that is, a transistor type switch. The solid state switch is becoming more and more economical, as the cost of semi-conductors continues to decrease, and offers probably far greater reliability and longer life than either of the other two types. Although tending downwards, the price is probably of the order of \$10 to \$30 per input at the present time.

Next in the system is the A/D converter, or encoder, as it is sometimes called. This device may be either an A/D converter or a digital voltmeter, which actually, are very similar devices. The digital voltmeter is normally a slower device, and frequently depends upon reed relays or stepping switches for its operation, although solid state type digital voltmeters are becoming more reasonable in price. Generally, the voltmeter includes a decimal display and operates with a binary coded decimal output which may or may not be useful in a particular telemetry system. The binary coded decimal output facilitates visual displays, but it is quite wasteful as far as hardware and bandwidth utilization is concerned. The natural binary output code is preferable when one doesn't really need the display feature. The digital voltmeter is typically capable of a maximum of about 10 to 100 readings per second, possibly up to 1,000 readings per second in some of the new devices. It is basically a DC measuring device, and is not particularly well-suited to AC measurements, although special AC interface accessories are available. The accuracy of the digital voltmeter, however, is normally specified with respect to its DC measuring characteristic. Accuracies of these devices are frequently overstated, and must be carefully examined before one decides what type of device to buy. Accuracies of the order of $\pm 0.01\%$ at fixed temperature on DC inputs is fairly readily available. However, these devices usually involve a temperature coefficient which is not included in their accuracy statement; and if one examines the accuracy over a temperature range, they find that accuracies more of the order of .05% to 0.1% are typical on DC measurements, and the errors may increase to as much as .25% to .5% on AC measurements.

It would be well to note that accuracy depends upon the total accumulated error of all elements of a system, and buying a .01% digital voltmeter as the basis for a system does not at all assure .01% accuracy on over-

all measurements. In fact, any well-designed system normally has the errors contributed by individual elements of the system balanced and distributed, so that each element contributes proportionately to the overall error. It is usually unwise to invest unduly in extreme precision in any one element. It is better and more economical to design the system for a practical overall accuracy level and proportion the individual errors throughout the system to permit purchase of practical system components, rather than highly sophisticated instruments that may or may not provide the desired results in actual practice. Accuracy costs money, and it is important not to require accuracies any higher than is absolutely necessary.

Recently, higher data rates are becoming involved, and systems do not utilize digital voltmeters, but use an A/D converter instead. A digital voltmeter is simply a special kind of A/D converter (A/D meaning: analog-to-digital). The A/D converter, however, does not usually have all the accessories and display features of the digital voltmeter, which are frequently unnecessary to the system. The A/D converter is a device that is more specifically designed for use in a PCM system, and is, therefore, usually more economical than the digital voltmeter. Furthermore, A/D converters do not have the speed limitations that are inherent with most digital voltmeters, and A/D converters having encoding speeds of the order of 1,000 to 100,000 inputs per second are not at all unreasonable in cost or complexity. The accuracy of A/D converters is essentially identical to digital voltmeters, except that it has, for some reason, become general practice to more correctly describe an A/D converter in terms of an accuracy over a temperature range, rather than at one fixed set of conditions. Accuracies of typical A/D converters range from .025% to .10% over quite wide temperature ranges of the order of 0 to 50°C, or even -54 to +70°C in some cases. These accuracies are particularly true if the A/D converter has what is called "sample and hold". Sample and hold is simply a very fast operating switch which connects the input to the measured quantity instantaneously, and then disconnects the voltmeter or A/D converter from the input quantity while the encoding is taking place; i.e., the encoder actually encodes a sample of the input quantity taken very quickly. This technique prevents the encoder accuracy from being affected by a continuously changing input, and is particularly important with rapidly changing signals. In some A/D converters, for instance, our own Bendix-Townson Laboratories' unit, the sample and hold

characteristic is an inherent feature, and comes automatically with the device. A block diagram of a typical Bendix ESD multiplexed data acquisition system (MDAS) is shown in Figure 3. Figure 4 and 5 illustrate the Bendix ESD approach to programmable gain amplifiers and solid state multiplexer devices.

Typical costs of digital voltmeters and A/D converters are very similar, except that the digital voltmeter is usually somewhat higher in cost, because it incorporates display features and frequently has its own power supplies and digital accessories not necessary to the system. Digital voltmeters are of the order of \$250 to \$1000 a unit, although some units with many special features frequently run as high as \$2000. A/D converters are typically of the order of \$150 to \$1000 a unit, and are tending toward lower prices, even with sample and hold features.

4.0 PCM TRANSMISSION CODES

Another important aspect of any PCM Telemetering system is the transmission code that is used to carry the information. A variety of code formats and waveforms are available to use for such transmissions, and the selection of the proper code is based upon a number of interrelated factors, among which are the following:

1. Utilization of the bandwidth of the transmitting medium. It is desirable to optimize signal to noise ratios to make it possible to use the lowest possible cost or tariff rate lines.
2. Error detecting codes may be required within the format to permit one to eliminate the effects of transmission noise bursts.
3. An important aspect of the code is the need to synchronize the data between the remote and the central station systems. That is, the system has to be able to identify the start and the end of a given reading to know what sensor is being read, and furthermore, has to know the start and the end of a given remote station's transmission to know what station is transmitting that particular piece of information. This identification and timing operation is termed synchronizing.
4. Another consideration is the specific frequency response characteristics of the transmission link being used. This factor influences the data rate that may be transmitted.

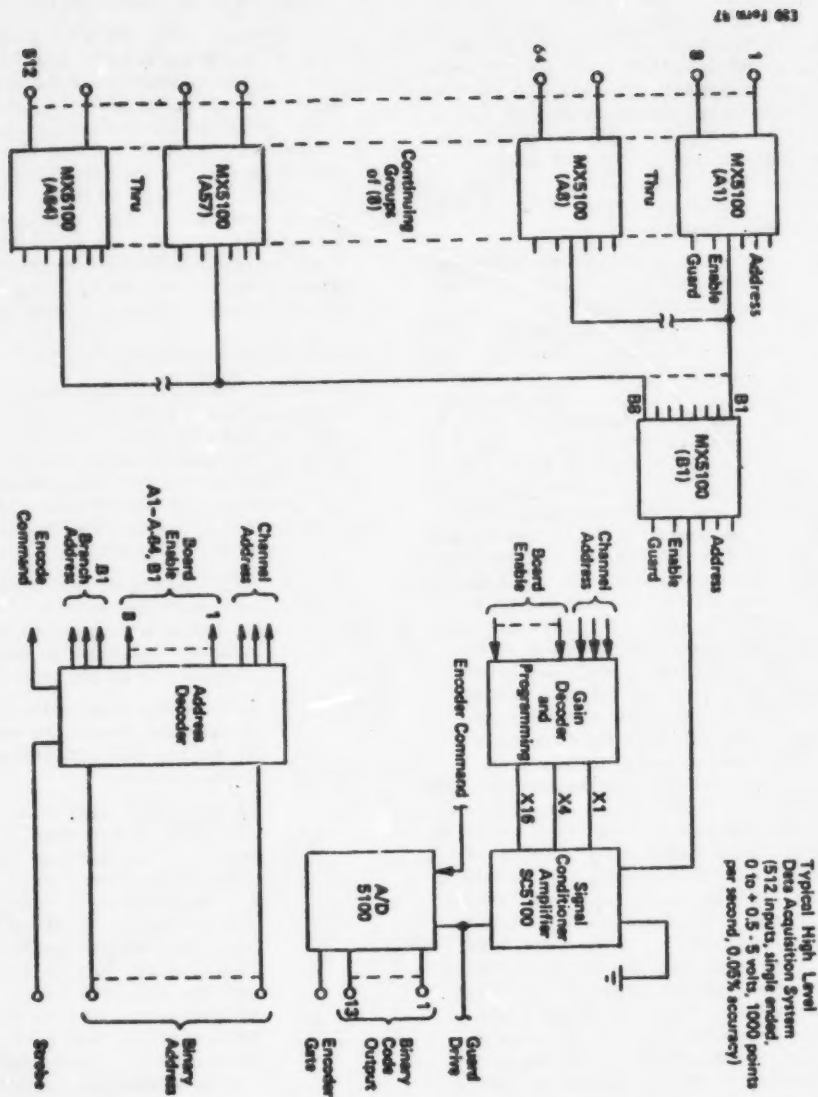


Figure 3

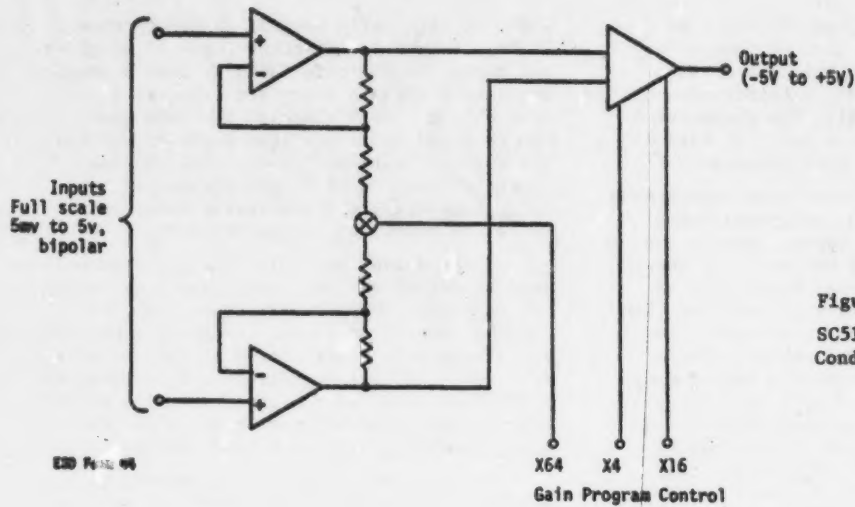


Figure 4
SC5100 Signal
Conditioning Amplifier

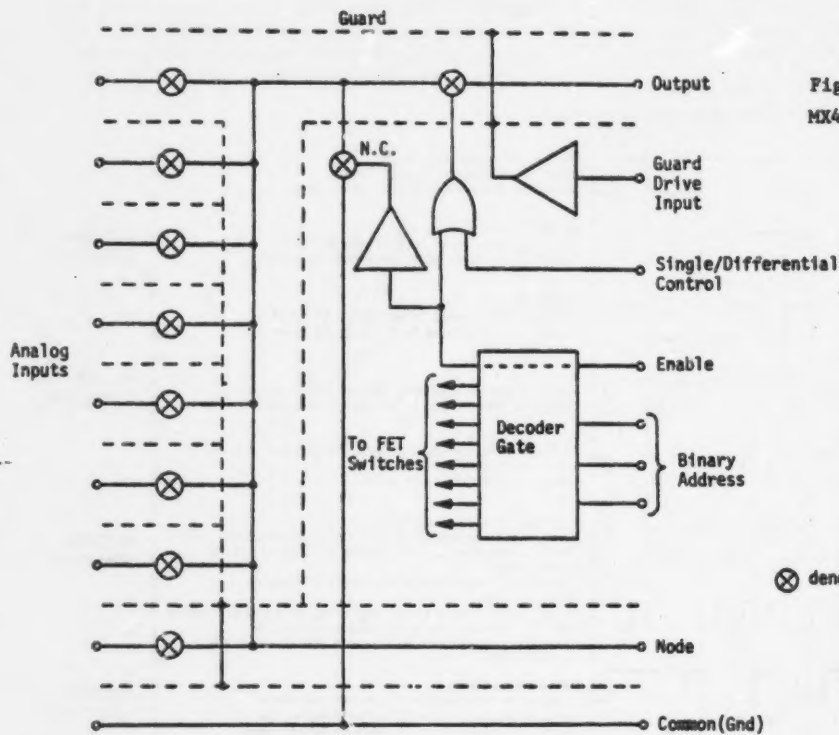


Figure 5
MX4100 Multiplexer Board

5. An arbitrary code may be required for a particular form of readout or display device at the central station; for instance, a teletypewriter is a case in point. The transmitted code has to be in a specific form to communicate with such devices.

The most frequently used code waveforms are shown in Figure 6. The waveforms break down into basically three types. One is the non-return-to-zero type or NRZ as it is known for short. There are several variations of the NRZ format, but the basic property of this waveform is that it does not necessarily return to zero during each bit period. Normally, a change in state occurs only when a code transition, either a 1 to 0 or 0 to 1, occurs. The NRZ type codes are important because they are the most frequently used, since they require a minimum bandwidth. Typically, the sinusoidal bandwidth may be as small as one-half of the NRZ bit rate that is to be transmitted. The NRZ waveform does have one important characteristic that must be considered, however, and that is that the bit clock information may not be present in the code being transmitted. In a digital system, it is necessary to transmit a bit clock to tell the computer, or other device at the central station, when to look at the signal being received to determine whether it is a 1 or a 0.

A second category of code waveforms

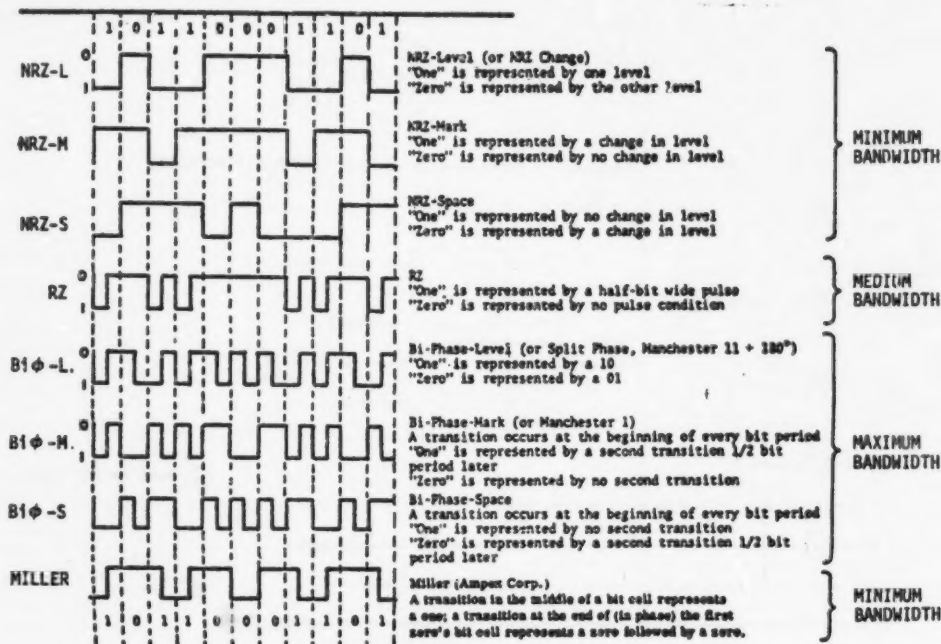


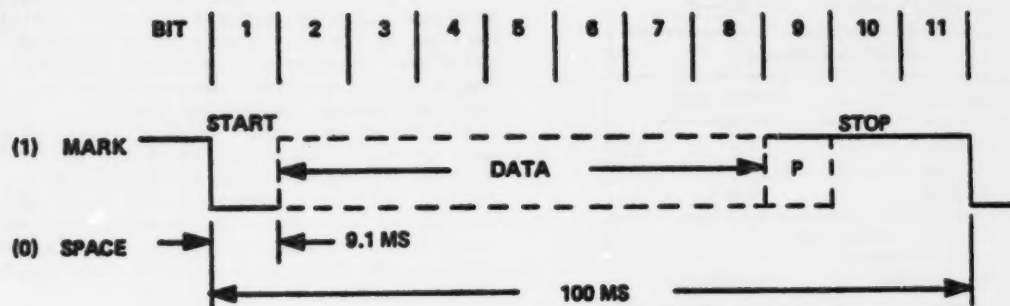
Figure 6

which is frequently used is called bi-phase. There are several different types of bi-phase, but the basic characteristic is that a change in state occurs in every bit interval regardless of the 1 or 0 state of the data code. The bi-phase codes are also known as Manchester codes. In this type of code, the bit clock information is always present in the code, however, the transmission requires twice the bandwidth of the NRZ code.

A third type that has recently been utilized is called a Miller code, which was originated by the AMPEX Corporation. In this code, a transition in the middle of a bit cell represents a 1; a transition at the end of the first 0's bit cell represents a 0 followed by a 0. This code has the same bandwidth properties as the other NRZ codes, but provides more dependable bit clock information.

In addition to the code waveform, it should be appreciated that there are certain standard codes that are frequently utilized for data transmission and computer activities.

One standard code that is probably familiar is the so-called five-level teletypewriter code. This is an arbitrary pulse code still required by older teletypewriters, but is rapidly becoming obsolete. The five-level code is being replaced in newer equipment by the so-called eight-level teletypewriter code, which, although it uses a longer code word,



8 LEVEL TELETYPEWRITER CODE
(USES 7 BIT ASCII DATA CODE)

Figure 7

incorporates a more fundamental code format, which is compatible with a much wider system capability than the five level teletypewriter code. The eight level teletypewriter code uses a seven bit standard ASCII data code as its foundation. ASCII stands for American Standard Code for Information Interchange, and is a standard established and widely utilized for communication between computers and computer devices. Frequently, the ASCII code is used by itself to communicate with or between computers. Figure 7 shows a typical eight level teletypewriter code. The teletypewriter code incorporates a unique synchronizing feature, which is peculiar to teletypewriter devices; that is, it is what is called a "start-stop" code. The device at the receiving end idles until such time as it receives a "start" pulse, then its synchronizing mechanism starts, and it accepts the succeeding pulse intervals. After a fixed number of pulse intervals, in this case - 8, including the parity bit, the device looks for a "stop" signal, and then stops its synchronizing action, and reverts to its idling condition, awaiting the next "start" pulse. This is an interrupted type of synchronizing method, and long gaps can exist between transmissions of information without effecting the synchronization of the system. In non-start-stop type systems, the system has to continue operating essentially all of the time, and information is being exchanged more or less continuously, whether data is being updated or not. The ASCII code does not incorporate "start-stop"

features, and it is necessary to add specific synchronizing codes periodically into the bit stream, in order for the system to work. The ASCII synchronizing codes can take many different forms; in fact, there is a wide degree of freedom of choice of codes, depending upon the computer programming. The synchronizing codes take on various degrees of complexity, depending upon the sophistication of the system with regard to utilization of transmission bandwidth, data handling speeds, minimization of errors due to noise bursts in the transmission line. Codes can involve various complex error detection techniques to eliminate errors due to the transmission link; however, this type of complexity is not usually necessary for telemetry operations, because the validity of any one piece of information is not all important as it sometimes is in a computer communication.

5.0 MODEMS AND COMMUNICATION FACILITIES

The next principle element of the system is the modem and the communication facility itself. These are highly standardized facilities that, for the most part, are available as a complete communication network, particularly if the network is a standard telephone line.

Some of the properties of present day telephone lines are shown in Figure 8. The table shows the standard nomenclature designating categories of telephone lines and their frequency/amplitude characteristics. This ta-

ATTENUATION CHARACTERISTICS Frequency Response, reference 1000 Hz ⁰⁰ :	
Unconditioned Channel	
Frequency range (Hz)	Variation (dB)
300-3000	-3 to +12
500-2500	-2 to +8
C1 Conditioning	
Frequency range (Hz)	Variation (dB)
300-2700†	-2 to +6
1000-2400†	-1 to +3
2700-3000	-3 to +12
C2 Conditioning	
Frequency range (Hz)	Variation (dB)
300-3000†	-2 to +6
500-2800†	-1 to +3
C4 Conditioning	
Frequency range (Hz)	Variation (dB)
300-3200†	-2 to +6
1500-3000†	-2 to +3

Measured between 600 ohm impedance at lineup, recommended value: 16 ±1 dB @ 1000 Hz

Figure 8

ble is included for general background information, and points out that there are at least four categories of telephone lines which may be contracted for, all of which have different capabilities. The modem is typically a frequency shift key device, in which the incoming pulse, or lack of a pulse, causes the modem to put out one frequency or another. In other words, the digital 1 may be one frequency, the digital 0 would be shifted from that to some other frequency. Another version of this FSK type transmission is called "tone-modulated" multiple levels, where numerals may be transmitted by transmitting specific tones as in the "touch tone" telephone dial system. A third type of telephone

line, of course, is the DC coupled type, which is usually available only as a private line for dedicated purposes. The DC coupled type is, of course, necessary for the very first type of telemetry system discussed - the amplitude modulated type system. The telephone system has special facilities set aside for teletypewriter communication and a teletypewriter modem, or interface, can be utilized for telemetry information by causing the teletypewriter itself to transmit numerals in accordance with a measurement derived from a sensor. Special A/D converters have been designed to accomplish this specific type of encoding.

The comments concerning telephone line characteristics apply similarly to radio-links except that, in general, radio-links have greater bandwidth capabilities, and therefore, permit greater flexibility with regard to data rates and interfacing requirements.

Typical costs for this section of the system are variable, depending upon whether the modem and communications equipment is purchased, or whether it is leased, as is frequently done with the telephone companies. As a rough approximation, a frequency shift keyed modem would probably run on the order of \$100 to \$250 per station, but it might be rented for a great deal less, perhaps \$10 to \$25 per month. Teletypewriters are a very inexpensive device, because of the frequency with which they are used. They typically run \$300 to \$500 per station, or again, they may be rented for approximately one tenth the purchase price.

6.0 PROGRAMMER/CONTROLLER

The last major element of the remote system is the programmer/controller, or the device that accomplishes the clocking and timing of all of the station operations. If the remote station operates on a random access or a polled basis, the programmer/controller recognizes its own incoming digital code, and starts a locally controlled clock, reading out the sensor inputs. Such a readout may be either one input at a time, upon command from the central station, or it might be made up of a complete frame, initiated by the central station. A frame consists of a readout of each one of the transducers or sensors at the remote station in proper sequence. The readout from the remote station almost invariably must include a code identifying that particular station and/or the frame or sensor that is being transmitted at a particular time.

It is possible to eliminate need for such a code if the central station is programmed to

add this identification to the data as it is received from the remote station. The bit structure of the interchange between the central and the remote station must, as previously mentioned, include both word and bit synchronizing features.

The exact makeup of a programmer/controller is very flexible, and depends greatly upon the basic operating features of the system itself. The programmer/controller may incorporate pulse error detection to minimize the effects of line noise, and circuits to add parity bit for checking the transmission at the receiving point. As previously mentioned, under code formats, an alternate synchronizing method that is frequently used between remote and central stations is the so-called "start-stop" code like the teletypewriter code. "Start-stop" codes facilitate repetitive non-poll type operation of the system, since any station can initiate data transmission. Typical costs for remote station programmer/controllers vary greatly, depending upon the requirements imposed on the system, but, in general, would range between \$200 and \$2,000 per station.

7.0 CENTRAL STATION

The central station is considerably less complex than the remote station, because the central station basically consists of a computer which readily polls the outlying stations, stores the incoming data, performs arithmetic operations on the data, annotates or identifies the data, provides automatic alarms for operators at pre-determined thresholds, and provides an output suitable to drive recorders or display devices. The data output characteristics at the central station may employ several alternate devices, depending upon how the data is to be used. One output unit is a paper tape punch, which is generally capable of punching ten characters per second. Another alternative is a teletypewriter readout, which provides both hard printed copy and punched tape, if desired. The teletypewriter is very easy to read, but is a relatively slow speed device, and provides up to about 2.5 readouts per second (based on ten characters per second and four decimal digits per reading). Another alternative is to record the information for later processing using a magnetic tape recorder. Tape recorders are capable of very high recording data rates, easily 200 to 2,000,000 characters per second, depending upon the type of recorder involved. Another output device is the strip printer, which prints numeric characters at 100 to 1,000 characters per second, but the strip printer usually requires

considerable data formatting and digital storage to control its operation. The most versatile, but perhaps most expensive, output display device is a cathode-ray tube display, which has essentially no speed limitations, and presents analog or graphic or alpha-numeric readout, with great flexibility, and facilitates "quick look" editing. The CRT display is, however, very expensive and not justifiable for slower data rate systems. Typical costs for a central station depend greatly upon what one expects of it, but would generally run in the range of \$5,000 to \$50,000 per station, depending upon the degree of sophistication.

SUMMARY

In telemetry meteorological data, first choose the basic type of telemetry system to be used. Present day technology results in the PCM telemetry system being the most frequently used approach. PCM, although somewhat more complicated in application, offers the advantage of high data rates, high accuracy of transmission, efficient utilization of communications facilities, and complete independence from the characteristics of the transmission or communication facility as regards accuracy. The PCM system utilizes codes that are directly computer compatible, thereby facilitating computer control and processing of the data. The choice of communication network characteristics that is required by the system has to be considered in the light of the data rates involved, and the operating expense objectives for the system. The code formats and waveforms to be utilized are related to the bandwidth, and, furthermore, must be selected to be compatible with the particular computer or other special readout device that may be utilized at the central station. In general, a system whereby the central station polls the outlying stations, requesting an updating upon command, is the more effective way of implementing telemetry data systems. Typical costs for system components have been described, but it is apparent that with the steadily decreasing costs for solid state devices, the trend will be more and more toward complete solid state implementation of these meteorological data telemetry systems.

Section Eight

DATA REDUCTION

Meteorological Data Reduction and Presentation Techniques

Meteorological Data Reduction and Presentation Techniques

James L. Dicke

I INTRODUCTION

What is the purpose of data analysis?

1. Determine current status of air pollution.
2. Describe the dispersion climatology of the region.
3. Determine patterns of air flow over the region.
4. Determine time variation of meteorology and air quality.
5. Determine geographic variation of meteorology and air quality.
6. Locate principal sources and receptor areas.
7. Determine causes of high pollution levels.
8. Estimate future trends in air quality.
9. Offer recommendations for abatement; regional planning.
10. Forecast and verification of air quality levels in episode situations.
11. Support special research studies.

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II BASIC PRINCIPLES OF SYSTEMS ENGINEERING (3) (24)

- A. Ascertain and specify precisely what is to be measured, when where and why.
 1. Range of the spectrum of each variable -
 2. Appropriate averaging times -
 3. Portion of complete cycle during which information is needed -
- B. Specify the procedures to be used in data transmission.
 1. Data rates -
 2. Mobility -
 3. Expandability -
 4. Costs -
- C. Analyze data recording and data processing requirements. (7) (13)
- D. Analyze requirements for display of processed information. (20)

Meteorological Data Reduction and Presentation Techniques

III GUIDELINES FOR RELEVANT TIME SAMPLING (16)

- A. Purpose of the investigation -
- B. Length of the observation period -
- C. Frequency of observation within the period -
- D. Averaging time of individual observations -
- E. Lag time of one variable with respect to another -
- F. Choice of the best index of time variability when an empirical method is used -
- G. Variation in environmental cycles -
- H. Non-linear interactions -

IV SPACE GUIDELINES IN SAMPLING NETWORK DESIGN (16)

- A. Purpose of the investigation -
- B. Nature of the underlying surface -
- C. Spatial variations of the sources -
- D. Spatial variations in the number of receptors -
- E. Practical limitations, e.g. accessibility, power, protection, budget -

V PHILOSOPHY OF DATA PROCESSING AND ANALYSIS (6) (24)

- A. Know the physics of the situation before choosing a meaningful variable or parameter for statistical analysis.
- B. Know something about the observations, e.g. instrument, observer, etc. (10) (13)
- C. Understand the method of processing the data before attempting to interpret the results. (20)

VI TECHNIQUES OF REDUCTION, ANALYSIS AND PRESENTATION

- A. Arithmetic (1) (14) (16) (18)
- B. Semi-logarithmic (24)
- C. Logarithmic - Concentration vs. Distance
- D. Polar (11) (15) (19) (21) (22) (25) (26)
- E. Cycles (USWB - LAAPCD) (6)
- F. Trends (8)
- G. Models (3)
- H. Statistics (2) (17)
 - 1. Regression (23)
 - 2. Correlation (23)
 - 3. Contingency (16)
 - 4. Probability (9)
 - 5. Trends (8)
- I. Graphic Display
 - 1. Computer
 - a. Tabular (28)
 - b. Calcomp
 - c. SYMAP, SYMVU(12)
 - 2. CRT
 - 3. Other

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